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IRAS

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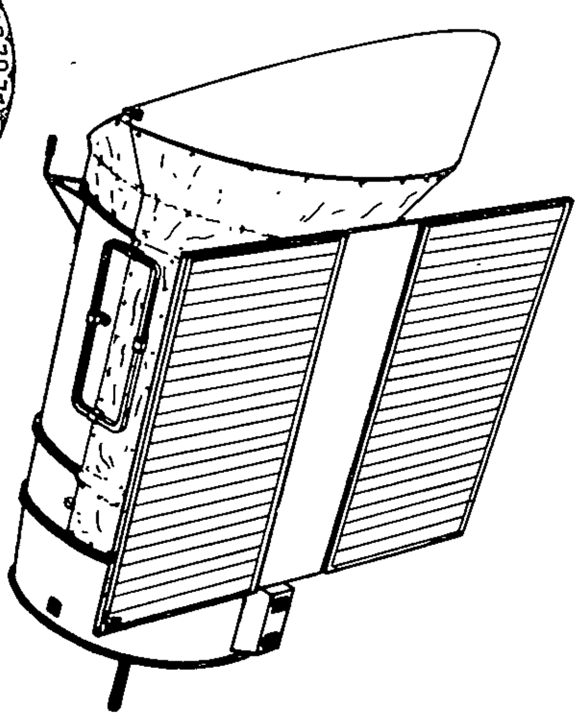
MAY 1976



REPORT OF THE JOINT

SCIENTIFIC MISSION DEFINITION TEAM

FOR AN

INFRARED ASTRONOMICAL SATELLITE

MAY 1976

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1. INTRODUCTION

Whenever a new spectral region has become available for astronomical observations, an unbiased sky survey has led to fundamental scientific advances. The National Geographic Society Palomar Sky Survey in the optical, the 3C and 4C Cambridge radio surveys and the UHURU X-ray survey are notable examples. The time is now ripe for a comparable survey of the sky at those infrared wavelengths at which a ground based all-sky survey is impossible. In this report we shall delineate the requirements for such a mission and describe one possible design which meets these requirements. It is a result of this study that the technical problems which have been anticipated for an infrared survey have been overcome by one or more solutions.

This report is the joint effort of scientists and engineers from the Netherlands, the United Kingdom and the United States working as a team formed in June 1975 for the purpose of exploring the possibility of a cooperative venture of this kind. This report draws upon work and earlier reports by the Industrial Consortium for the Infrared Astronomical Satellite (ICIRAS) ("IRAS Concept Description, December, 1975"), by the Hughes Aircraft Company, and by Ball Brothers Research Corporation.

The proposed mission builds upon experience gained from the succesful Astronomical Netherlands Satellite (ANS). Like ANS, this satellite will be in a polar orbit at an altitude of 900 km. It will carry an 0.6 m diameter telescope cooled with helium to a temperature near 10K. An array of about $\sim$ 100 detectors will be used to measure the infrared flux in 4 wavelength bands centered at 10, 20, 50 and 100 μm. The sensitivity of all but the latter channel should be set by the photon fluctations in the flux from the zodiacal light. Sources will be located on the sky with positional accuracy of 1/2 arcminute. The instrument should be able to

investigate the structure of extended sources with angular scales up to 1°.

The entire sky will be surveyed by combining a restricted pointing capability of the telescope with the orbital motion of the spacecraft. To ensure confidence in source detection and identification it will be necessary to repeat observations on time scales of seconds, hours, weeks and months. About fifty percent of the sky will be covered within the first few weeks, but the full lifetime of the mission of about one year will be necessary to complete the survey.

Apart from the survey, approximately 40 percent of the time will be available for special observational programs. The prime objectives of these are to improve the classification of sources found in the survey by low resolution spectroscopy and extension of the wavelength coverage to longer wavelengths. These additional instruments will operate along with the survey.

Quick access to the data will permit interaction with the satellite observing program. Complete survey data will be reduced and released to the scientific community as quickly as is compatible with achieving a reliable survey.

The most important conclusion of the report is that a highly sensitive satellite survey is fully feasible at this time. The main points leading to this conclusion are as follows:

a. The engineering and technical problems of providing the necessary cryogenic temperatures for a long duration flight have been shown to be solvable.

b. The effects of high energy charged particle radiation on sensitive infrared detectors have been carefully studied and circumvention techniques have been developed.

c. Progress in the development and application of suitable infrared detectors is sufficient to guarantee background limited performance at most wavelengths.

d. Large arrays of infrared detectors and their associated signal processing and data systems have been studied and shown to be straight-forward extrapolations of existing systems.

e. The feasibility of retrieving and analysing the large amounts of data produced by a fast highly reliable survey has been demonstrated.

f. It has been shown that a scientifically important and significant all sky survey can be carried out within reasonable cost and schedule constraints.

The sensitivity limits of the survey will be set by fundamental limits imposed on any near-earth orbiting infrared observatory. Hence the survey should provide a definitive and exciting view of the universe as seen at infrared wavelengths.

II. SCIENTIFIC OBJECTIVES

A. SURVEY

Although infrared astronomy has thus far been limited primarily to studying objects discovered at other wavelengths, it is producing major contributions to the understanding of many areas of astrophysics. In galactic astronomy these areas include the origin, constitution, and replenishment of interstellar matter (both gas and grains), the problem of star formation, and the energy balance in ionized hydrogen (H II) regions and molecular clouds. In extragalactic research, infrared observations indicate that many extragalactic sources, both normal galaxies and more peculiar and explosive sources, emit copiously in the infrared, many radiating the bulk of their luminosity at infrared wavelengths. Understanding the origins of this luminosity and the emission mechanisms responsible is among the most pressing of current astrophysical problems.

While we know from these studies that many astrophysically interesting objects are copious producers of infrared energy, we do not know how significant the infrared region of the spectrum is to the energy budget of the universe as a whole. This is because no sensitive, all-sky survey has been made throughout most of the infrared. Existing infrared surveys (CIT at 2 μm, AFCRL at 4, 11 and 20 μm) are dominated by sources essentially stellar in nature and are not sufficiently sensitive to insure the discovery of all important classes of infrared emitters at 11 μm and 20 μm; at these wavelengths the proposed IRAS survey is at least 1000 times more sensitive than the AFCRL survey. There is no all-sky survey in the far infrared (λ >30 μm).

Only a cooled space telescope, with its low background environment, allows a high sensitivity, all-sky survey to be conducted in a realistic period (1/2 to 1 year). In this report we describe such

a sky survey mission which presents a unique opportunity to accumulate a wealth of astrophysically important information about the infrared sky. Determination of the properties of various types of discrete sources, their frequency of occurrence and their distribution on the sky is a crucial objective which only an unbiased survey can accomplish. Furthermore, we already know that many infrared sources are most luminous at wavelengths inaccessible from the ground. Study of the nature and energetics of these sources will be possible since the survey spans the bulk of the infrared spectrum.

The sensitivity of this instrument for detecting infrared sources is shown in figure 2.1. Here we have plotted the minimum detectable bolometric luminosity as a function of temperature (assuming a blackbody emission) for typical galactic and extragalactic distances. The limiting fluxes have been calculated using conservative limits for achievable sensitivities. In the two short wavelength channels these are set by the zodiacal background and therefore represent near ultimate performance for a fast, all-sky survey at these wavelengths from a near earth platform. For the two longer wavelength channels the sensitivity is determined by conservative extrapolation of detector performance. If the detector studies presently underway prove successful, an order of magnitude or more improvement in the survey limits for the long wavelegnths is possible. From this plot it is clear that any known important infrared emitters in the Galaxy will be detected in the survey. Some of the areas where the survey may contribute significantly to galactic and extragalactic astronomy are described below.

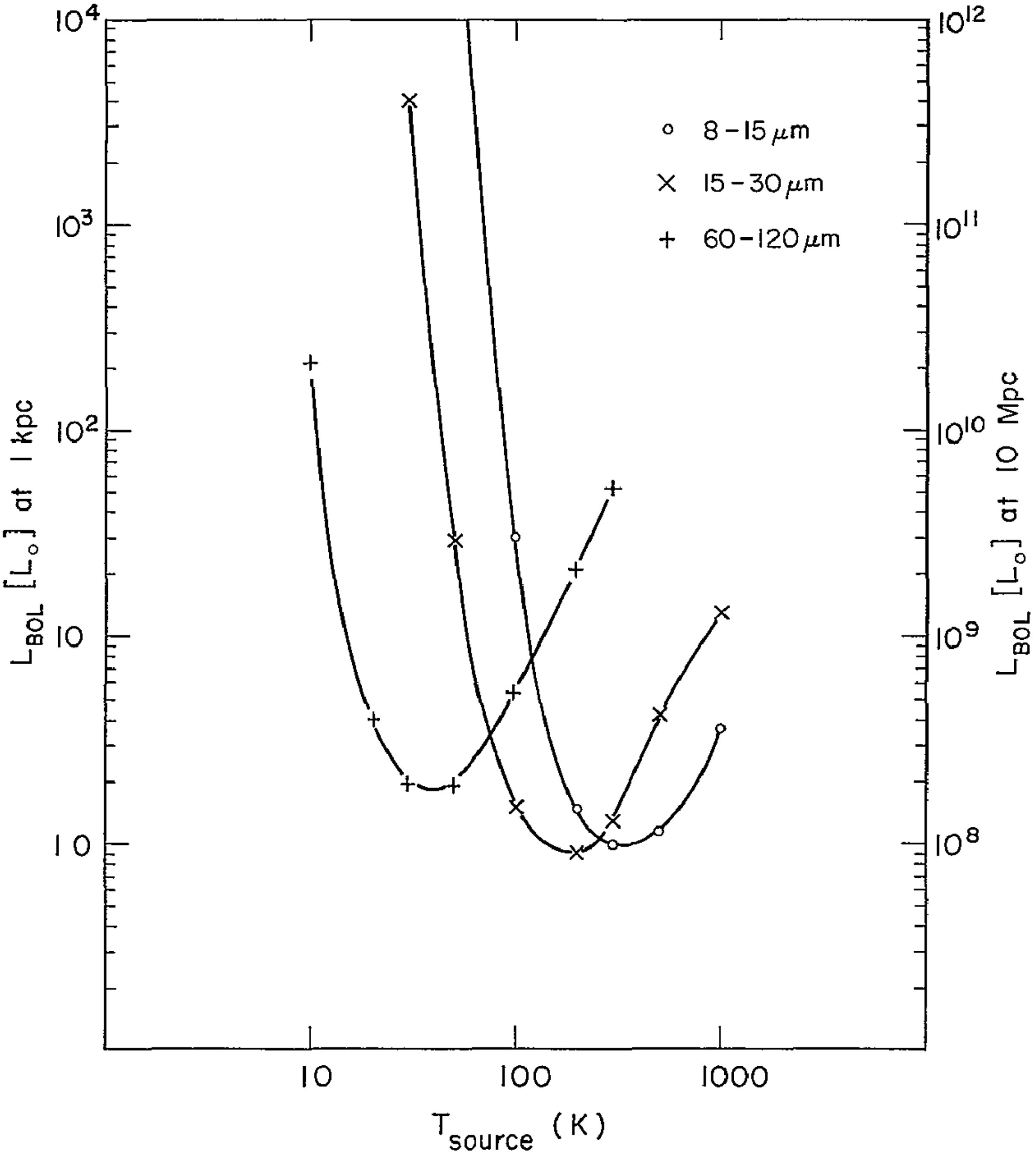

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Figure 2.1. Minimum Detectable Bolometric Luminosity
At Distances of 1 kpc and 10 Mpc

GALACTIC ASTRONOMY

In galactic astronomy, the importance of the survey lies in the Galaxy's relative transparency to infrared radiation, which circumvents to a large extent the difficult problem of interstellar extinction. Table 2.1. shows the distances to which specific interesting infrared objects, previously studied from ground, balloon, and airborne observatories, could be seen at the proposed survey sensitivity limits. The blank entries are an indication that no measurements at that wavelength are available.

The study of the origin and energetics of interstellar grains is one of the major contributions of infrared astronomy. The material formed in, and ejected from, evolved stellar objects is thought to dominate the resupplying of the interstellar medium with newly processed matter. Through infrared observations it is possible to determine mass-loss rates in these objects, and as can be seen from table 2.1., the survey would detect a significant fraction of all such objects in the Galaxy if they are similar to the nearby objects αLyr, αOri, OCet and IRC + 10216. We can therefore envisage actually measuring the rate of replenishment of matter in the interstellar medium from stars in the later stages of evolution.

The BN object in Orion is the prototype of a class of objects thought to be in clouds collapsing to form stars. At the limiting sensitivity of the survey, all such objects in the Galaxy could be detected. Indeed, theoretical model calculations suggest that the infrared survey could detect protostellar objects as small as 1 $M_\odot$ over a substantial fraction of the Galaxy. We can hope to measure directly the rate of star formation in the Galaxy.

Many H II regions are, as the presence of very young stars demonstrates, regions of recent or ongoing star formation. The Trapezium region of Orion is a fairly ordinary H II region, important

Table 2.1. Maximum Distance at Which Known Objects Would Be Seen by Survey

Object	Class	Actual Distance	Max. dist. detectable at λ with baseline system		
			10 µ (8-15 µ) .06 Jy†	20 µ (15-30 µ) .1 Jy†	100 µ (75-125 µ) 2 Jy†
Solar System					
Asteroid at 300K	3 km diameter		1 AU		
Galactic Sources					
α Lyr	AO V star	8 pc	180 pc**	56 pc	
α Ori	M supergiant	.2 kpc	90 kpc**	25 kpc	
o Cet	Mira variable	.04 kpc	8 kpc**	5 kpc	
IRC + 10216	Carbon star large in IR excess	.3 kpc	300 kpc**	32 kpc	
BN	"protostar"	.5 kpc	35 kpc	30 kpc	
KL neb. in Orion	"IR star cluster" large silicate absorption	.5 kpc		100 kpc	
NGC 7027	planetary nebular bright in IR	1.7 kpc	80 kpc		
Trapezium	Typical H II region-no silicate absorption	.5 kpc	50 kpc	50 kpc	
W51-IRS 1	Giant H II region/mole cloud large silicate absorption	.6 kpc	240 kpc	580 kpc	1600 kpc (all of W51)
W51-IRS 2	Giant H II region/mole cloud mod. silicate absorption	.6 kpc	410 kpc	750 kpc	
M17	Giant H II region. Bright near IR	1.6 kpc	940 kpc	1700 kpc	600 kpc
OMC 2	Molecular cloud w/imbedded near IR sources	.5 kpc	15 kpc	13 kpc	20 kpc
ρ Oph Dark Cloud	Dark cloud/mole cloud	.15 kpc			15 kpc
Sgr B2	Giant H II/mole cloud	10 kpc			5 Mpc
Galactic Center		10 kpc	4 Mpc	2.5 Mpc	12 Mpc
Extragalactic Sources					
NGC 253	Spiral galaxy. Some nuclear activity	2.4 Mpc	35 Mpc	60 Mpc	70 Mpc
M82	Dust galaxy. Some evidence for explosive activity	3 Mpc	50 Mpc	70 Mpc	80 Mpc
NGC 1068	Seyfert galaxy	22 Mpc	340 Mpc	400 Mpc	230 Mpc
Mk 231	Markarian galaxy	230 Mpc	1100 Mpc		
3 C 273	Quasi-stellar object-variable	950 Mpc* v/c = .16	3300 Mpc* v/c = 0.5	3300 Mpc	

† limit for detection with signal-to-noise of 10:1 on proposed survey.
* assuming redshift is cosmological
** assuming no interstellar 10 µm absorption

primarily because of its proximity to us. All such regions, to the distance of the Magellanic Clouds, could be detected in the survey. In fact, all H II regions identified in the many radio surveys of the galactic plane should be detectable at all survey wavelengths if the crude relation of the ratio of radio to infrared flux found for the brighter ones extend to the lowest radio flux levels. In addition, giant H II regions, such as M17, W51 and Sgr B2, would be detectable at distances beyond M31.

In the last several years radio observations have shown that vast molecular clouds are quite common in the Galaxy. Many of these clouds are cold ($T \sim 10K$), and are evidently in the earliest stages of collapse. With the survey we shall be able to observe many such collapsing clouds, including the extremely cold ones, as well as all the larger molecular cloud complexes in the Galaxy as luminous as OMC-2. Dark clouds such as the ρ Oph complex will be detectable throughout most of the Galaxy.

Since all the known important galactic infrared emitters will be detectable over virtually the entire Galaxy, the survey will add significantly to understanding the overall structure and evolution of the Galaxy. The survey will detect stars over the entire Galaxy and should contribute to our understanding of galactic structure. Nearly all regions of current star formation in the Galaxy will be located, providing a better understanding of the current evolution of the Galaxy. Finally, the measurement of the infrared luminosity of the Galaxy _in toto_ will permit a comparison with the infrared emission of other galaxies.

EXTRAGALACTIC ASTRONOMY

Infrared observations have already shown that the power outputs of many visual, extragalactic objects are dominated by their infrared emission.

In extragalactic astronomy the importance of the all-sky survey is twofold; by extending to reasonable distance scales the sample of objects measured, it will establish in an unbiased way the significance of infrared emitters in the universe, and secondly it will provide observations vital to the understanding of infrared emission mechanisms. Table 2.1. shows what can be expected from the survey for a selection of extragalactic sources.

Our galactic center, a comparatively weak infrared source, could be detected as far away as the nearest major spirals. Somewhat stronger infrared emitters, such as NGC 253 and M82, could be detected well beyond the Virgo Cluster, the largest nearby cluster of galaxies. The very brightest (in the infrared) Seyfert galaxies, such as NGC 1068, would be detectable to 400 Mpc, farther than many of the well studied clusters of galaxies. The most luminous infrared galaxy known, Mk 231, could be seen to 1100 Mpc, beyond the clusters of galaxies catalogued by Abell. One of the brightest known quasi-stellar objects, 3C 273, could be detected to 3 times its distance (or a redshift of 0.5 if the redshifts are cosmological). In selected areas, in clusters of galaxies for example, deep surveys could be made to a flux limit at least one order of magnitude lower than in the main survey.

Extending the study of extragalactic objects in an unbiased way to these cosmic distance scales is essential in evaluating the importance of infrared emission in the observable universe. It is also extremely important to understand the mechanisms responsible for infrared emission in extragalactic objects. Several extragalactic infrared sources can be accounted for by thermal radiation, while others require more exotic emission mechanisms. It is reasonable to expect that classification of extragalactic sources on the basis of infrared spectra will be possible, leading to a better understanding of the relative numbers of the different types of extragalactic infrared sources. Further insight into the radiation

mechanisms will emerge from the study of the infrared spectra in the non-thermal sources.

NEW CLASSES OF PURELY INFRARED OBJECTS

A very exciting aspect of the all-sky survey is the possible discovery of new classes of sources which emit their energy almost entirely at infrared wavelengths. A few such objects have been discovered in the previous infrared surveys; IRAS will be sufficiently sensitive and reliable that many more such sources should be found, enabling us to do statistical studies on their properties. As figure 2.1. demonstrates, a small source with a temperature between 10 and 1000 K and luminosities $\sim 1 L_{\odot}$ will be detected if within 1 kpc of the Sun. Low mass, very cool stars within 100 pc will be detected if their luminosity exceeds 10^{-2} $L_{\odot}$.

An example of an almost purely infrared source is CRL 2688, a strong infrared source that has been discovered in the AFCFL survey and is possibly the missing link between carbon stars and planetary nebula. It is visible on photographic plates but its unusual characteristics were noticed only because of its infrared properties.

In the realm of galaxies, completely new objects may be found. It is conceivable that very cool galaxies exist. If so, a luminous object with a bolometric luminosity of 10^6 $L_{\odot}$ (compared with 10^{11} $L_{\odot}$ for a normal spiral) will be detected out to the distance of M31. By doing a survey in a small part of the sky and using larger integration times it will be possible to reach much deeper into space. For instance, a deep survey in the Virgo cluster could detect extremely low luminosity infrared galaxies.

II. SCIENTIFIC OBJECTIVES

B. ADDITIONAL INSTRUMENTS

The following additional experiments have been considered to supplement the main survey;

a. Low resolution spectroscopy

b. Long wavelength photometric measurements

c. Measurement of cosmic background radiation

d. High resolution spectrometry.

The first two experiments are considered desirable and feasible within the constraints of the mission.

The latter two experiments, although of high scientific value were, regrettably, not considered suitable for IRAS because of engineering and budget constraints.

a. Low Resolution Spectroscopy

Ground-based studies of galactic sources of infrared radiation have shown that a number of relatively broadband spectral features appear in the wavelength range of the IRAS survey. Such features are attributed to solid state resonances in dust particles. Therefore, the study of low resolution spectra contributes to the understanding of the composition and origin of interstellar solid material. As an example, the well known "silicate" feature at 9.7 μm is so pronounced that it will considerably influence the broadband 8 - 15 μm observations in the survey. Similar features are expected to appear in the whole range 7 - 50 μm. A spectrometer of modest

resolution and/or a series of narrow band filters exploits the increased sensitivity offered by the cold telescope and the space environment.

A major scientific benefit of this experiment will be the classification of sources found in the survey, on the basis of their infrared spectra.

b. Long-wavelength Photometer

Wavelengths between 8 and 120 μm are already covered in the four survey bands. It is desirable to include a fifth channel covering the range 120 to 300 μm. If the sensitivity of such a channel is comparable to that of the 100 μm channel, it would be extremely useful and allow a better estimate of the temperatures and total luminosities of the cooler sources. For example, sources with an effective temperature of 30K radiate as much energy between 120 and 300 μm as they do in the 100 μm survey channel.

c. Spectrum of the Cosmic Background Radiation

The infrared region of the spectrum includes the bulk of the energy of the relic background radiation thought to be a result of the primeval cosmic explosion. Measurements of the spectrum and angular distribution of this radiation are a powerful and probably unique window on conditions in the universe at its earliest epoch. A cryogenic spectrometer in space holds the promise of establishing the spectrum to the limit imposed by interstellar dust. The important issue is no longer to establish the existence of the radiation but rather to make a detailed determination of the spectrum, since deviations from a thermal spectrum would have profound implications for cosmology.

Unfortunately such an experiment is difficult to accommodate in the survey instrument. The extremely low side lobe requirements at millimeter and sub-millimeter wavelengths preclude carrying out the experiment in the focal plane of the survey telescope itself. The impact on the survey instrument of a separate instrument placed over the secondary is judged too serious to include the experiment in the IRAS mission.

d. High Resolution Spectroscopy

To understand the physical processes of the interstellar medium it is important to measure the radiation from both the gaseous phase and the dust. These two types of radiation can only be separated by high resolution spectroscopy ($\lambda/\Delta\lambda \sim 3000$). For this purpose a solid Fabry-Perot interferometer has many advantages; it has a large resolving power and is stable in operation. An important objective for this experiment would be the observation of the rotational transition of molecular hydrogen at 28 μm. Since a large fraction of interstellar gas is in the form of molecular hydrogen, direct observations of the 28 μm line would be extremely valuable in understanding the physical conditions in the interstellar medium. Other atomic lines that play an important role in the energy balance of the interstellar medium could be observed with the same instrument.

III. IRAS SCIENTIFIC FUNCTIONAL REQUIREMENTS

INTRODUCTION

This chapter describes the functional requirements of IRAS with emphasis on those requirements which result from the scientific objectives of the mission.

An attempt is made to define the key elements in the scientific objectives with special reference to those that seem to impact the design and drive the engineering efforts in the project. As much as possible, consideration has been given to engineering feasibility and cost although a cost trade-off has been made only at the close of the study. These requirements set targets for engineering development that can be met while at the same time providing the instrumental capabilities needed to fulfill the scientific objectives of the mission.

1. WAVELENGTH COVERAGE

The survey shall be conducted in four wavelength bands. The bandpasses are tentatively selected to have half power points at 8 and 15, 15 and 30, 30 and 60, 60 and 120 μm for the 10, 20, 50 and 100 μm bands respectively. The cut-on and cut-off wavelengths of each channel may be adjusted slightly to correspond to detector characteristics.

The integrated short wavelength response below the short wavelength 1% transmission point of a band shall be less than two percent of the in-band response for a 2000K blackbody source. Similarly, the integrated long wavelength response beyond the long wavelength 1% point of a band shall be less than two percent of the in-band response for a 200K blackbody source.

The selected wavelength range gives good coverage of the emission spectrum of most known infrared sources. The inclusion of both short and long wavelength channels allows the survey to be sensitive to all known infrared emission mechanisms.

2. SENSITIVITY

The experiment shall be designed in such a way that the limiting background is due to zodiacal dust emission. As described in chapter IV, with reasonable assumptions this corresponds to noise equivalent flux densities of 0.006, 0.01, 0.01 and 0.02 Jy at 10, 20, 50 and 100 μm.

The sensitivities quoted above are slight extrapolations of current technology for the 10 and 20 μm bands but, as described below, require significant detector development for the 50 and 100 μm bands. These sensitivities should be maintained within the constraints of stray light rejection as given in section 9. below. It should be noted that the nominal survey scan speed is 3.5 arcminute/sec.

3. IMAGE QUALITY

The diameter of the blur circle containing 80% of the energy from a point source for a wavelength of 0.5 μm should be less than 5 arcseconds over an unvignetted field of 42 arcminutes diameter. This guarantees that the requirements for positional accuracy can be met and that the optical aberrations are less than the diffraction image at all the infrared wavelengths.

4. POSITIONAL ACCURACY

Location of the position on the sky of point-like sources that have an instantaneous signal-to-noise ratio of twenty or higher shall be possible with an absolute (2σ) accuracy of ±0.5 arcminute for the 10 and 20 μm channels and 1 arcminute for the 50 and 100 μm channels.

This positional accuracy is needed to provide unambiguous identification with sources observed at other wavelengths and will permit follow-up observations by other techniques. Most importantly it allows for orbit-to-orbit source confirmation which is vital to the reliability of the survey. It should be noted that the spacecraft's attitude control system has a stated stability of better than ±10 arcseconds.

5. EXTENDED SOURCES

For an extended source of uniform brightness the reconstructed intensity assigned to any two points separated by 1° on the sky shall not differ by more than 10%, provided that these points give rise to a signal greater than 10 times the noise. This requirement extends the range of angular scale observed in the survey from arcminutes to a degree, thus covering a major part of the scale on which known astronomical phenomena are observed.

6. SKY COVERAGE-LIFETIME

The survey shall cover at least 80% of the sky in a 4 month period, with a minimum of 50 percent in the initial 10 to 20 day period, in such a manner that each area is seen on at least two orbits within a 24 hr. period. The survey shall be repeated to achieve high

reliability and to provide coverage on time scales of seconds, hours, weeks and five months. The operational lifetime (design goal) of the system is one year. The latter requirement allows for repetition of observations of certain areas of sky that were not observed or were poorly observed during the first half year, thus essentially completing the survey for the full sky. It also allows repetition of observations of newly detected objects or other sources that proved to be very interesting on the basis of the first survey, and a search for variability. Redundancy on the range of time scales described is necessary for the confirmation of sources, for the identification of moving sources, and for the statistical study of variability of infrared sources. The need for redundancy to increase the reliability of the survey is discussed in chapter VI.6. After an initial period devoted entirely to the survey, a significant fraction of the time, nominally 40%, shall be devoted to special observing programs.

7. RADIATION INTERFERENCE

Loss of the observations by ionizing radiation interference shall occur during less than fifteen percent of the period of a polar orbit that passes through the South Atlantic Anomaly. No significant degradation shall occur due to trapped electrons. The survey instrument shall therefore maintain the stated photometric accuracy and sensitivity performance for radiation levels external to the spacecraft of at least 10^3 trapped protons/cm^2 sec at proton energies of 50 MeV and higher. After passage through a zone of high level radiation the instrument shall be capable of resuming normal operating conditions in less than 60 seconds.

8. PHOTOMETRIC ACCURACY/DYNAMIC RANGE

As a goal the relative photometric error in the survey shall be less than five percent for point-like sources in all channels. This shall be achieved by careful in-orbit calibration of the instrument. The dynamic range of the survey channels shall be $10^5 : 1$ (maximum signal : rms noise).

9. STRAY LIGHT

The diffuse flux level in the focal plane due to the Earth and Sun at viewing angles up to 30° from the local vertical and 60° to the Sun shall not exceed ten percent of the zodiacal emission flux level in the focal plane for the short wavelength channels and 10% of the telescope emission in the 100 μm channel. The same shall apply for a viewing angle of 20° from the Moon.

10. CROSS TALK

Combined optical and electrical cross talk between nearest neighbors in the array shall be less than one percent. Crosstalk between all other detectors shall be less than 10^{-3}.

11. ADDITIONAL INSTRUMENTS - OTHER MODES

A. Low Resolution Spectroscopy

The objective of this additional instrument is to obtain low resolution spectra in the wavelength range from 7 to 50 μm in order, among other objectives, to aid in the classification of the sources found in the survey. Resolution required is 0.5 μm in the 9 - 12 μm

range. The entrance aperture will be half the array width to permit complete sky coverage (no overlap) in the survey mode. In the scan direction the width shall be 6 arcminutes or less to minimize source confusion.

B. Long Wavelength Channel

This channel will enable better estimates to be made of temperatures and total luminosities of sources, particularly of the cooler sources. A long wavelength channel shall be included with a wavelength range from 120 to 300 μm. The width of the channel in the cross-scan direction will be approximately half the survey width.

C. Total Flux

A measure of the bias current of one detector in each spectral band shall be used to determine the total flux incident on the focal plane in each wavelength channel.

Other Modes

The spacecraft will allow a variety of scan speeds, raster scan modes and pointing to enhance the utilization of the survey instrument and additional instruments. Deep sky surveys will be performed by adding repeated scans over the same areas. Short term variability will be studied in the pointing mode.

12. DATA STORAGE AND TRANSMISSION

The onboard data system shall be able to store and transmit 5×10^8 bits of scientific data per day at a bit error rate of $<10^{-5}$. The raw data are needed to guarantee flexibility and optimization of the data analysis, and to avoid the loss of significant discoveries due to preconceived data analysis algorithms. The relatively large volume of the data is the result of the great number of sources that the instrument will detect in each orbital scan. Estimates based on models of stellar distributions and extragalactic source densities indicate that of the order of 10,000 sources will be detected on each orbit. The nominal data transmission shall not interrupt the observations for more than 20 minutes per 12 hours.

An onboard data selection and storage system shall operate routinely to provide data for a fast evaluation of survey progress and performance.

13. DATA PROCESSING

Final processing of the survey experiment data shall be performed on the basis of the raw data. The end result of the survey consists of a data base that contains calibrated flux densities at all wavelengths observed during the survey in accordance with the requirements as stated in 3. and 4. All photometric entries in the data base shall be associated with information concerning the noise level pertinent to the observation. Copies and extractions of the data base according to various criteria shall be made available to the scientific community at low cost. For those observations that are performed outside the survey, processed data will be made available to the individuals or organizations that requested the observations on a priority basis.

14. OPERATIONS

The operations shall allow interaction by astronomers with the programming of satellite observations. Quick look results shall be made available in easily accessible formats. Processing of quick look data shall allow near-real time evaluation of survey progress, results of observations and performance of scientific instruments and satellite systems. Follow-up studies of interesting sources detected in the survey require a turn-around capability after first detection to subsequent observation of less than three weeks.

IV. CONCEPTUAL DESIGN

1. INTRODUCTION

This chapter shows that the functional requirements detailed in chapter III. are feasible using existing technology and reasonable extrapolations thereof. A self-consistent conceptual design is presented which meets the stated functional requirements. Of the many alternatives considered in this study, several appear satisfactory. A formal design phase will be required to define the final instrument configuration. It should be emphasized that this conceptual design is not intended to be final but only to demonstrate the feasibility of the scientific requirements.

2. GENERAL CONFIGURATION

Figure 4.1. shows the general features of the design. The 0.6 m diameter telescope with attached focal plane package is mounted rigidly to the cryogen tanks and the whole package - including shields, baffles and internal insulation - is enclosed in a vacuum-tight case. Prior to launch, and during an initial outgassing period in orbit, the vacuum inside the case is maintained by a cryogenically cooled cover which is ultimately jettisoned. During launch, the telescope and cryogen tanks are supported by retractable supports; much less rigid supports are left in place after launch. To reduce aperture loading and improve shielding from the Sun and Earth, there are radiatively cooled shields as shown in figure 4.1. Table 4.1. summarizes weights. A beryllium alloy Cassegrain telescope provides a light weight, strong, compact system with good off-axis rejection. It is cooled by a hybrid helium cryogen giving a 12 month lifetime. The telescope feeds four broadband survey

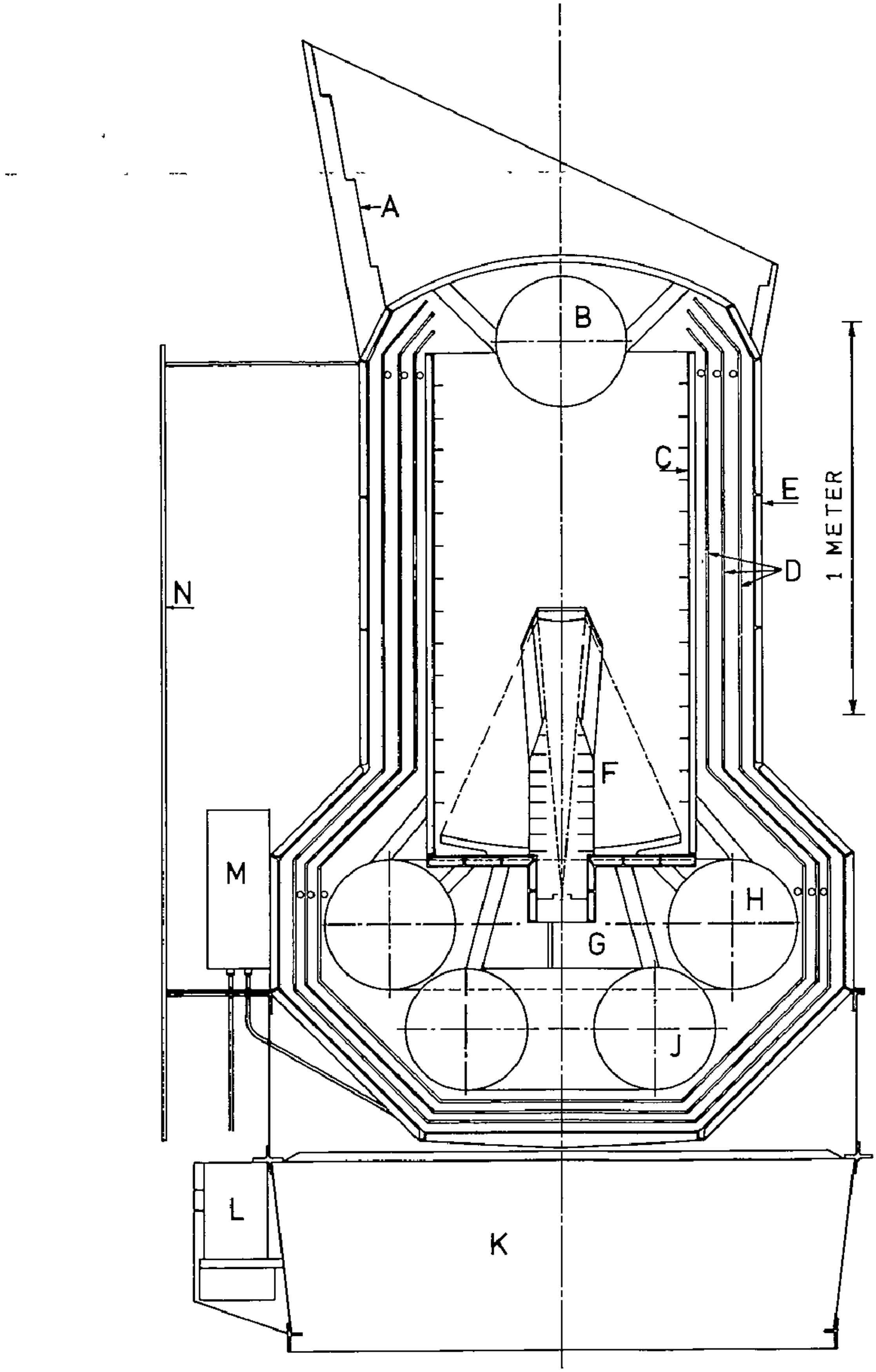

Figure 4.1 General Layout of the Infrared Astronomy Survey Satellite

Figure 4.1. - <u>General Layout Legend</u>

A.	Sun-Earth Shield	(<100K)
B.	Removable Cover	(5.3 - 10K)
C.	Main Telescope Baffle	(5.3 - 16K)
D.	Radiation Shields and Multi-layer Insulation	
E.	Dewar Outer Shell	(200K)
F.	Telescope	(3 - 10K)
G.	Focal Plane Assembly	(3K)
H.	Supercritical Tank	(3 atm, 5.3 - 16K, 37 kg, 340 liters)
J.	Superfluid Tank	(.02 atm, 1.8K, 13 kg, 90 liters)
K.	Spacecraft, basic structure and subsystems	
L.	Attitude Control Package	
M.	Experiment Electronics	
N.	Solar Panel	

Experiment		Weight (kg)	
Dewar Outer Shell		150	
SF He Tank		5	
SC He Tank		22	
Vapor-cooled Shields		26	
Supports and Insulation		50	
Plumbing and Valves		18	
Telescope		27	
Focal Plane Assembly		10	
Main Telescope Baffle		18	
Sun-Earth Shield		32	
Spacecraft Adaptor		34	
Electronics and Wiring		32	
Ejection Cover		25	
Cryogen		50	
	Total:	499	499
Spacecraft			
Basic Structure		74	
Subsystems		185	
	Total:	259	259
		Total:	758
Margin (10%)			76
		TOTAL WEIGHT:	834

Table 4.1. - Approximate Weights of IRAS Satellite

channels in the focal plane, covering 8 μm to 120 μm, operating as closely as possible to the fundamental background limits. There is also room in the focal plane for additional experiments.

3. TELESCOPE OPTICS

a. Size

The aperture of 0.6 m was chosen to provide the best possible angular resolution and sensitivity consistent with size and weight limitations imposed by the Delta launch system. At 10 μm the diffraction limited resolution, about 8 arc seconds, is roughly equal to the pointing stability of the spacecraft.

b. Optical System

In addition to the usual requirements for an optical system, it is necessary to consider here the rejection of out-of-field radiation from a number of sources. Both Cassegrain and Gregorian systems have been studied. The relatively compact 2-mirror Cassegrain system shown in figure 4.1. was chosen over the larger 4-mirror folded Gregorian because it achieves adequate off axis rejection (see fig. 4.2.), is more compact and has a smaller central obscuration. In making this choice, both scattering and diffraction were considered. The secondary is supported from the primary baffle tube in order to minimize scattering from the supports. In addition, the obscuration by the supports must be minimized because of their diffraction effects.

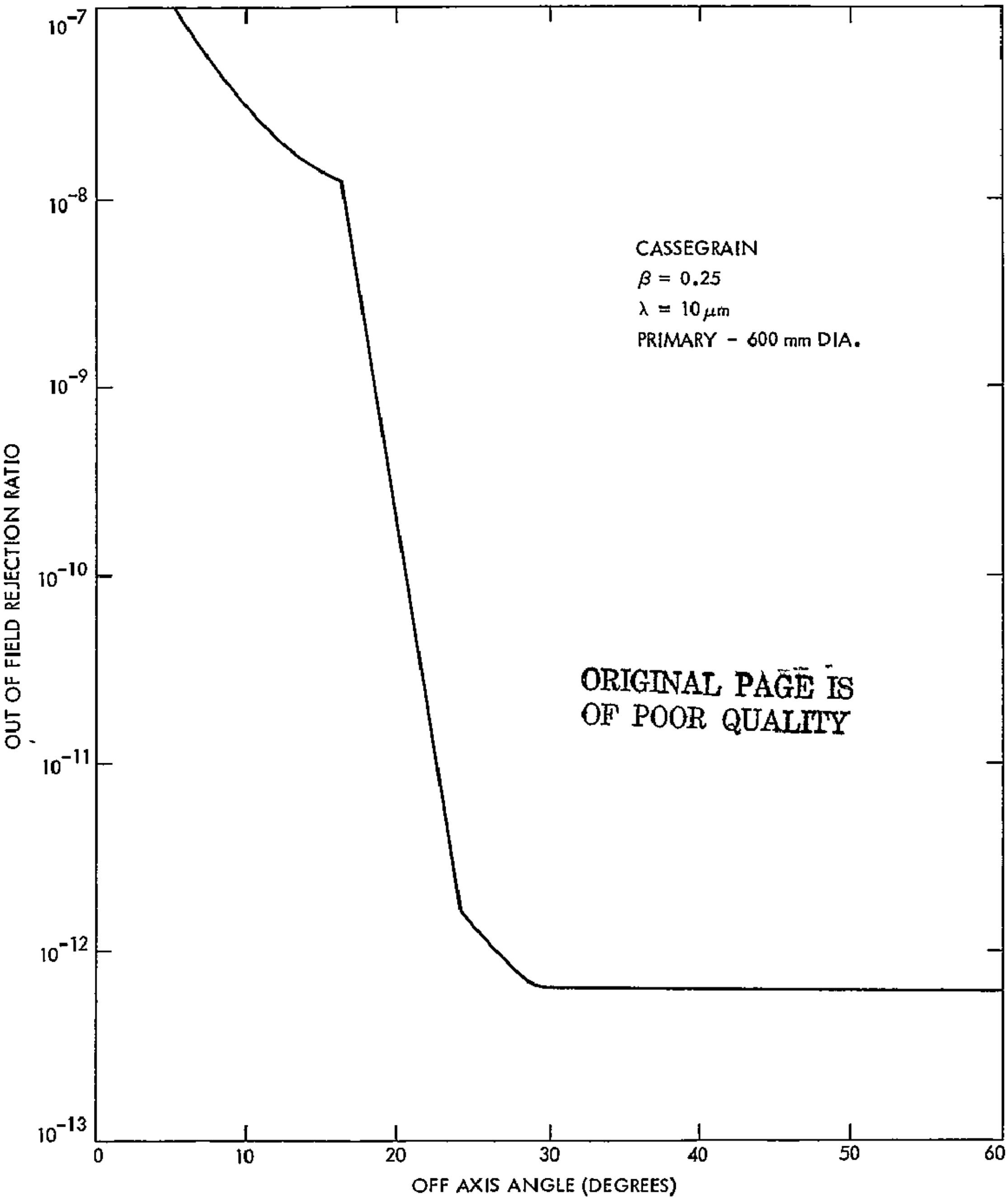

Figure 4.2 Off Axis Rejection Profile

c. Image Quality and Diffraction

Diffraction dominates geometrical aberration over the entire field of view at the wavelengths of interest in this survey.

d. Field Properties

The basic survey requirement is for a 30 arcminutes square field. Thus a flat unvignetted field 42 arcminutes in diameter is required.

e. Focal Lengths

Table 4.2. summarizes the dimensions of the optical system. A compact instrument is desirable from several viewpoints; however the focal plane scale of 0.6 arcminute/mm and effective focal ratio of f/10 were chosen in order to provide adequate area and volume, and to accommodate the detector arrays and their associated amplifiers, field optics and filters.

f. Optical Materials

Beryllium alloys will be used for both mirrors and their supports. Experience with other large cooled telescopes clearly demonstrates the stability of Be systems.

4. CRYOGENIC SYSTEM

The performance of large dewars using vapor-cooled radiation shields and multilayer insulation ("super insulation") has now been amply demonstrated. In calculating the performance of this

Primary Diameter	600 mm
Primary Focal Length	600 mm
Secondary Diameter	73 mm
Secondary Focal Length	73 mm
Effective Focal Length	6190 mm
Effective Focal Ratio	10
Focal Plane Scale	0.56 arcminutes/mm
Back Focal Distance	150 mm
Central Obscuration Ratio	0.25
Unvignetted Field Diameter	42 arcminutes
Blur Circle Diameter	5 arcseconds

Table 4.2. - Parameters of the Cassegrain Optical System

conceptual design, no significant improvements have been assumed relative to existing systems. As refinements in cryogenic engineering take place, we can expect further reduction of parasitic losses.

Table 4.3. lists the calculated heat loads and temperatures for the conceptual design. There are three low temperature domains: (1) 3K for the detectors and their associated preamplifiers, field optics and filters, (2) 10K for the optics, and (3) 16K for the telescope baffle. The relatively small superfluid dewar provides cooling for the focal plane instruments by conduction. The evolving gas provides the cooling to maintain the telescope optics below 10K. The cooling available in warming the gas from 10K to 16K is used to maintain the shield which surrounds the entire 3K apparatus at 16K. This shield is attached to the telescope baffle. A relatively large (37 kg, i.e., 340 liter) supercritical tank pressurized to 3 atm. provides this cooling in two parts. At the beginning of the mission the tank contains 37 kg of helium at 5.2K; at the end of the mission the tank contains 4 kg of helium at 8K. The evolving gas (33 kg) passes through a heat exchanger attached to the 16K baffle and shield. The mass of supercritical helium needed to provide an average of 50 mW cooling for a one year lifetime is approximately 20 kg. The mass of supercritical helium in the baseline configuration was increased to 37 kg to account for the mass flow dependence of the heat load. A careful distribution of the load between the supercritical tank and the heat exchanger must be maintained. In this hybrid system, the best qualities of both the superfluid and supercritical systems have been exploited. The volume of superfluid is relatively small and should not cause concern even though it is a two-fluid system (gas phase plus liquid phase). The feasibility of large cryogenic systems of this type is discussed in detail in chapter VI.

1.8 - 3 K		
100 Detectors		5 mw
Supports and Leads		2 mw
Margin		3 mw
	Total:	10 mw
5 - 10 K		
Telescope		
Conduction		3 mw
Radiation		3 mw
	Total:	6 mw
5.2 - 16 K		
Radiation		6 mw
Supports		23 mw
Aperture Load		15 mw
Margin		6 mw
	Total:	50 mw

Table 4.3. - Projected Heat Loads

5. FOCAL PLANE

A. Survey Channels

i. Layout of the Array

The focal plane layout is shown in figure 4.3. and a summary of the pertinent parameters is given in table 4.4. In addition to the four basic survey channels containing 67 detectors the focal plane includes visual star aspect sensors and two additional instruments as described below.

ii. Electrical Bandwidth and Data Rate

The electrical bandwidth is determined both by the orbital scan rate and the requirements of observing extended sources, the latter requiring a response down to 0.01 Hz. Sampling is performed at a rate of 4 samples per dwell time for a point source. Bandwidths, sampling frequencies and resultant bit rates are given in table 4.4.

iii. Positional Accuracy

The geometry of the focal plane and the data sampling rate contribute to the uncertainty in the coordinates of an observed source. If a source is observed on one detector only, its position in the "cross-scan" direction must lie between adjacent detectors. Assuming the source has equal probability of being anywhere in the interval leads to a root mean square uncertainty of the non-overlapped width divided by $\sqrt{12}$. In the "in scan" direction, the position of a source is given by the measurement of the time at which it transits the detector. If the transit is regarded as the time of peak

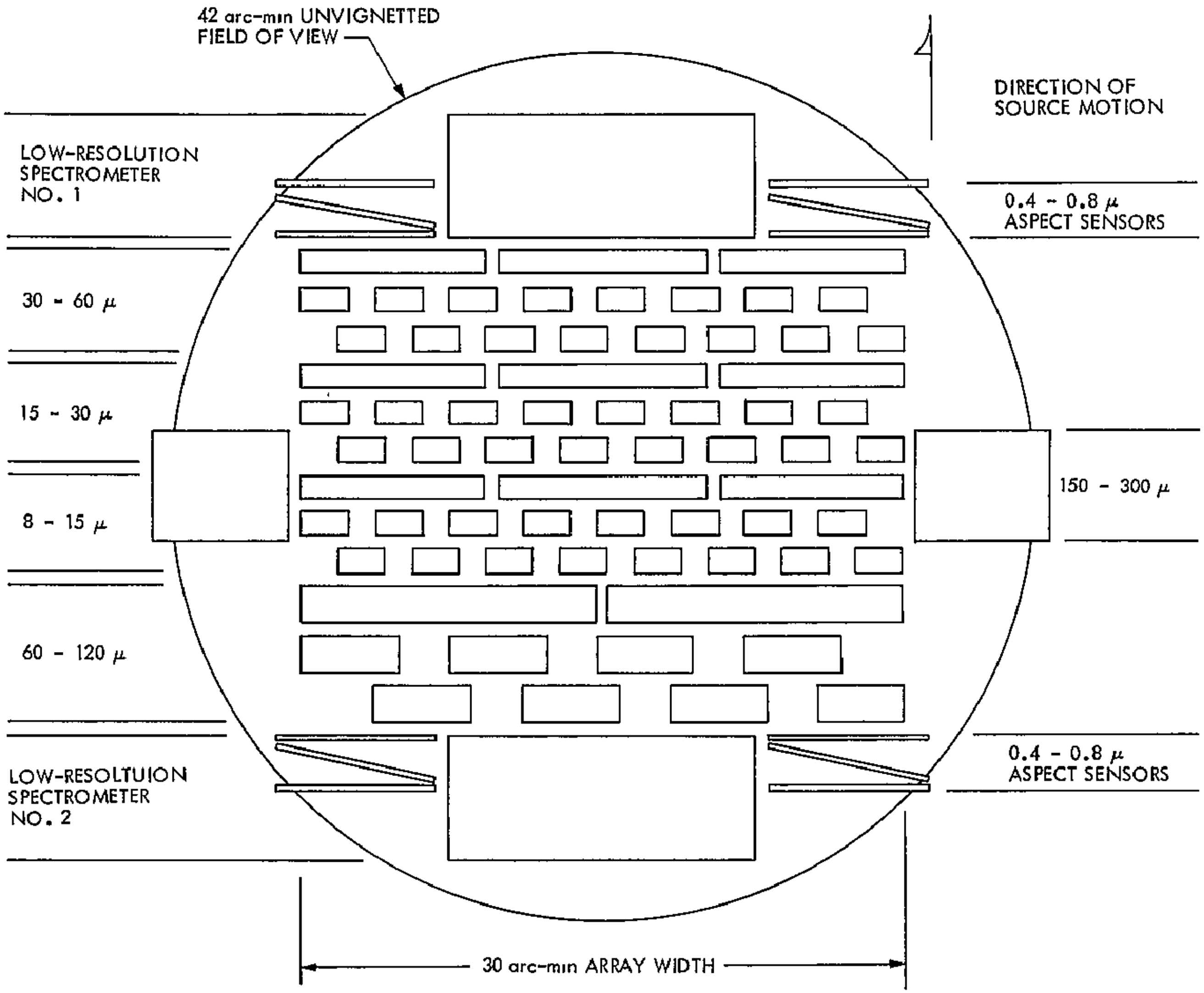

Figure 4.3. Focal Plane Layout

Spectral Band (microns)	Detector Material	No.	Dimensions* (arcmin)	Bandwidth (Hz)	Samples (per sec)	Bit Rate (bits/day)
8 - 15	Si:As	19	1.2 x 2.4	1.4	12	1.6×10^8
15 - 30	Si:Sb	19	1.2 x 2.4	1.4	12	1.6×10^8
30 - 60	Ge:Be	19	1.2 x 2.4	1.4	12	1.6×10^8
60 -120	Ge:Ga	10	1.8 x 4.8	1.0	8	5.5×10^7
150 -300	Bolometer	2	5 x 7	.3	2	3.5×10^5
Low Resolution Spectrometers		-	6 x 15	-	-	4.0×10^6
Total Focal Plane Data Rate						5.4×10^8
Visual Aspect Sensors		12	0.5 x 10	-	-	-

*Smallest detectors of channel.

Table 4.4. - Baseline Focal Plane Array

amplitude of the signal, the uncertainty in measuring this time is ± one sample interval. This analysis leads to a root mean square uncertainty in the "in-scan" direction of the orbital scan rate divided by $\sqrt{3}$ times the sampling rate. Results for each channel are given in table 4.5. The total errors include spacecraft limit cycle errors.

iv. Detectors

The IRAS survey array requires detectors with high sensitivity over broad spectral regions. Operation of these detectors in the low background photon environment of a cryogenic telescope viewing a space background favors the use of photoconductive devices. Table 4.6. lists the detectors selected for the baseline system, the applicable wavelength band, operating temperature, quantum efficiency and current responsivity averaged over the spectral band. The data for the silicon detectors (Si:As, Si:Sb) are measured state-of-the-art values supplied by detector manufacturers. The data tabulated for the long wavelength germanium detectors (Ge:Be, Ge:Ga) are values projected by Santa Barbara Research Center to be achieved in their present development program.

v. Survey Sensitivity

The survey is designed to be limited by background photon noise. The survey detectors are used in a transimpedance amplifier input circuit with a cryogenic MOSFET preamplifier and warm operational amplifier; it is important that the noise from the detector load resistor and the MOSFET are less than the zodiacal light noise. Table 4.7. gives the zodiacal light limited noise equivalent flux density (NEFD) and noise equivalent spectral density (NESD) for the four survey channels. It should be noted that the zodiacal light

Band (μm)	Array Errors [(1)] in scan	x-scan	Total Error [(2)] in scan	x-scan
8 - 15	11	21	0.4	0.7
15 - 30	11	21	0.4	0.7
30 - 60	11	21	0.4	0.7
60 -120	15	42	0.5	1.4

(1) arcseconds, 1σ

(2) arcminutes, 2σ

Table 4.5. - Positional Errors

Channel	Detector Material	Detector Characteristics						Background Limited NEP* (watt/$Hz^{\frac{1}{2}}$)	f (Hz)
		Ionization Energy E_i (eV)	Long Wavelength Cut Off (µm)	Operating Temperature (K)	Responsivity (amp/watt)	Quantum Efficiency			
8 - 15 µm	Si:As	0.054	23	14	3.4	35%		1.2×10^{-16}	≤2.9
15 - 30 µm	Si:Sb	0.043	29	12	3.8	30%		7.8×10^{-17}	≤1.4
30 - 60 µm	Ge:Be	0.024	52	6.6	1.2	15%		4.3×10^{-17}	≤ .7
60 -120 µm	Ge:Ga	0.01	120	3.3	1.9	8%		2.2×10^{-17}	≤ .4

*Zodiacal light only.

Table 4.6. - Summary of the Characteristics of the Detectors Selected for the Conceptual Design

Band	ECLIPTIC		POLE	
	NEFD	NESD	NEFD	NESD
8 - 15	1.1×10^{-19}	0.007	6.9×10^{-20}	0.005
15 - 30	8.3×10^{-20}	0.010	5.0×10^{-20}	0.006
30 - 60	4.7×10^{-20}	0.011	3.2×10^{-20}	0.007
60 -120	4.2×10^{-20}	0.018	3.9×10^{-20}	0.013

NEFD in watts/cm^2

NESD in Janskys (1 Jy = 10^{-26} watts/m^{2}Hz)

Table 4.7. - System Sensitivity

limited NESD for the long wavelength channels is 10-30 times smaller than the NESD assumed in chapters II. and III. This reflects the large uncertainty in performance of these as yet unproven detectors and indicates the potential sensitivity improvements if the detector development is successful.

vi. Field Optics and Detector Size

All the survey array detectors use Fabry optics for two reasons: to improve the photometric accuracy through uniform detector illumination and to reduce the physical dimensions of the detector element, thus reducing its cross-section for interaction with high energy radiation. At longer wavelengths field lenses will make possible the use of integrating cavities to increase the effective quantum efficiency. A number of optical materials can be used in each of the four spectral bands. Fabrication of small rectangular lenses of the sizes required for IRAS is routine for vendors specializing in this type of fabrication. The lenses can be accurately positioned and bonded into a honeycomb structure forming a well-aligned self-supporting structure with metal cells which extend below the lenses to prevent optical crosstalk.

vii. Optical Filters

Bandpass filters for the four survey bands can be made using conventional dielectric interference filter techniques and all will have average in-band transmittances greater than 75%. The 100 μm band will require additional developmental work.

B. Additional Instruments

i. Long-wavelength Channel

The scientific requirement is for detectors responsive out to 300 μm wavelength at a sensitivity comparable to that in the 60 - 120 μm channel. Available data show that thermal detectors are at present more promising than photoconductors. At 3K a conventional germanium bolometer will have an electrical NEP of $\sim 2 \times 10^{-14}$ W/Hz$^{1/2}$. Improvements by as much as an order of magnitude are projected for several new types of bolometers under development.

The channel is designed to be diffraction limited at 300 μm so that a 15 arcminutes field of view is covered by 2 detectors. This channel will be of value for cool sources, where an appreciable amount of the power is at wavelengths longer than 100 μm. A low-pass mesh filter is proposed to block the power at shorter wavelengths.

ii. Low Resolution Spectroscopy

The basic instrument is a modified Czerny-Turner spectrograph using aspheric collimator and camera mirrors. The entrance aperture is 6 arcminutes long in the scan direction and 15 arcminutes wide. In the present concept, three orders are used to cover a total spectral range of 6.8 to 21.2 μm; each order will have three detectors, allowing a spatial resolution of about 6 arcminutes in the cross scan direction. By increasing the number of detectors the field of view can be reduced, which results in a higher sensitivity and less confusion.

The resolving power is determined by the detector aperture size. The minimum detector size depends on the edge-of-field spectrometer image quality which, for the telescope described above, results in a resolving power on the order of 25. A 0.60 m telescope can easily accommodate a spectrometer with the required resolution. The instrument could conceivably operate both during the survey and, with enhanced sensitivity, in a raster scan mode. Using the survey mode, the instrument would generally produce spectra with reasonable signal to noise ($\sim$10) for all objects which produce a signal to noise ratio of $\sim$300 in the corresponding survey channel.

The same objectives, with some development work, could be met using a much less complex linear variable filter in the telescope focal plane. An effective resolving power of 10 could be obtained in this way.

iii. Infrared Background Measurements

For engineering purposes and for verification of the instrumental performance it is necessary to monitor the bias current from at least one detector in each channel. This monitors infrared backgrounds of astronomical and diagnostic interest.

6. MODULATION SCHEMES

In the conceptual design outlined above, the modulation of the infrared flux is provided by the scan motion of the satellite.

Several other modulation schemes have been considered during the design study and further study may show that some of these are superior to the scheme chosen. In particular, the possibility of using square wave beam switching must be considered. Such modulation would provide a characteristic source signature and raise the signal frequency (to $\sim$15 Hz) thus decreasing the likelihood of spurious signals from low frequency disturbances. Although in such a scheme it might be difficult to remove spurious radiation signals, it provides the system with the ability to perform long term integration on selected regions of the sky. A possible alternative to the present scheme is to provide a beam switching capability which is or is not used as dictated by initial performance. In fact, the focal plane array of figure 4.3. is well suited for detecting signals either using beam switching or modulation via the scan motion.

Such alternative modulation schemes are being investigated further.

7. SIGNAL PROCESSING ELECTRONICS

1. Detector Input Circuit

The detector input circuit is a frequency compensated current-mode amplifier. Its primary functions are to provide an impedance transformation down from the detector impedance of about 10^{13} ohm, and extend the system bandwidth relative to that obtainable with conventional source follower amplifier. The wideband response of the current mode amplifier is necessary to achieve suppression of short duration pulses due to high energy particles.

ii. High Energy Particle Hit Suppresion

Charged particles passing through or stopping in a detector produce impulses in the detector output. A typical proton event results in the deposition of about 1 MeV in the detector; this event results in a voltage spike 10^3 times the noise level in a 300 Hz bandwidth. With a preamplifier response time of 1 msec, a pulse will have a duration of only 10 msec. A number of feasible schemes for removing the pulses caused by radiation hits have been proposed; all depend on the fast rise time and short duration of radiation hit pulses compared to the rise time and duration of the signal produced by true celestial sources. The particular scheme adopted for the conceptual design uses a relatively simple analog circuit to distinguish radiation pulses based on measuring their rise times. The signal is then held at the level immediately preceeding a pulse for an amount of time which depends on the size of the pulse. Since the dwell time of real signals is 0.3 sec, several tens of hits/sec can be removed without significant loss of data. The predicted pulse rates and detector response characteristics are more fully discussed in chapter VI where it is shown that such a suppression system is more than adequate.

iii. Bandlimiting Filter

The frequency response of the direct coupled system is limited by a conventional low pass filter with high frequency cut-off optimized for the dwell time of a point source. A d.c. system periodically resets the output of the electronics to zero and thus minimizes baseline drift and preserves low frequency response to 0.001 Hz.

iv. Multiplexer and Analog to Digital Converter

The output of each amplifier chain is coupled into an analogue multiplexer feeding a precision 8 bit analog to digital converter. The multiplexer is programmable through the onboard computer. The digitization level for each channel will be set by a variable gain amplifier feeding the analog to digital converter.

8. DATA PROCESSING

The ultimate objective of the data processing is to produce a reliable data base from the IRAS survey which can be used in astrophysical research. This requirement necessitates the creation from the data base of several standard outputs that are suitable for maximum distribution and use in the general astronomical community. The full data base can be made available to researchers desiring to work on special problems.

In the present concept two data streams can be distinguished, the raw experiment data (5×10^8 bits/day) and a processed stream of 10^6 bits/day. The 10^6 bit/day data stream is used as the quick response monitor of spacecraft and experiment performance. Quick look scientific data is extracted from the raw data for rapid satellite response to interesting scientific discoveries. Figure 4.4. shows a block diagram of the data processing flow.

8.1. Orbit Determination

Orbit determination will be performed only for purposes of data acquisition and spacecraft operations at the IRAS ground station and control center.

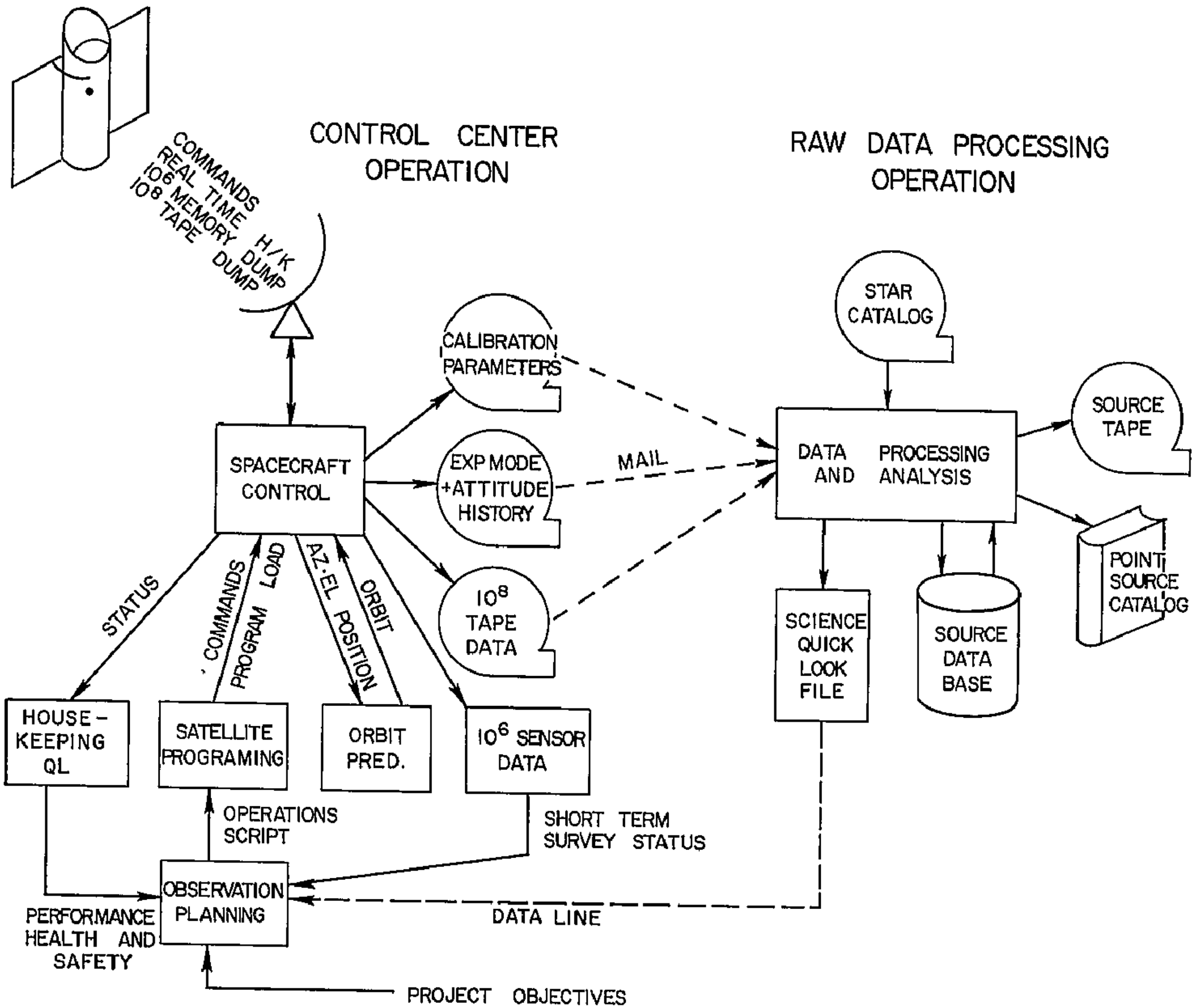

Figure 4.4 IRAS Data Flow

8.2. Control Center Operations

The IRAS control center will be located at Appleton Laboratory, Slough, U.K. and will be responsible for IRAS operations control, data acquisition, orbit determination, attitude determination, satellite programming, spacecraft computer programming and quick-look processing. A joint science operations team will be located at the control center.

8.3. Data Processing Operations

The IRAS data reduction and data analysis will be performed in the U.S. These activities will include the transformation of raw experimental, housekeeping and attitude information into final data products for distribution to the astronomical community. These products include a series of IRAS source catalogs in printed form and on digital magnetic tape. Periodic quick-look science data will also be produced for the purpose of providing the science operations team with information concerning the current status of the survey.

8.4. Data Acquisition

All IRAS data will be acquired at the IRAS ground station. The low bit rate real-time and solid-state memory data will be used for control center operations and quick-look purposes. The raw experiment data will be recorded on tape. This tape will be shipped to the data processing center responsible for IRAS data reduction.

8.5. Attitude Determination

Spacecraft attitude will be determined by the IRAS control center using data acquired from low bit rate real-time and solid-state memory data. These data will be processed to produce an experiment mode and attitude history of the IRAS telescope on a 1600 bpi digital magnetic tape. This tape will be mailed to the IRAS Data Analysis Center. It may be necessary to determine higher accuracy attitude information using data from the spacecraft tape recorder data.

8.6. Housekeeping Quick Look Data

The performance of the telescope detector array will be continuously monitored by the IRAS control center. Information concerning each detector's status and calibration will be periodically listed as part of the spacecraft Health and Safety Analysis by the control center. A time history of each detector's status and calibration will be sent to the IRAS Data Analysis Facility for use by them in production of final data products. The performance, health, and safety of the spacecraft will also be continuously monitored through the memory dump data. Both spacecraft and sensor performance will be supplied to the IRAS operations control on a short time scale (less than 1 day).

8.7. IRAS Observation Planning

The satellite observation planning will take place at the IRAS control center. The engineering quick look data will provide rapid mission performance information to insure the complete sky coverage on an orbit to orbit basis. The scientific quick-look will be

provided to the IRAS control center so that detailed survey quality can be monitored and incomplete or inferior quality coverage repeated. In addition, changes in the mission in reaction to discoveries will be determined here.

8.8. Experiment Data Processing

The experiment will generate 5×10^8 bits/day of raw data that must be processed at a very nearly real time rate to keep up with the survey. The processing center will be provided with tapes of satellite data dumps. The processing flow is shown in figure 4.5.

The digital tape must first have the data quality verified and formatted for further processing. This is done in the cleaning process. Aspect information and data from secondary experiments will be removed at this stage and written on separate tapes for further processing. The survey channels data base will be written on a tape in the most effective format for further processing.

Two processing paths are followed after the data is cleaned. The first produces rapid turnaround data for the purpose of

a. monitoring progress and quality of the survey, and if necessary, revising the observing program,

b. inspecting data for important new astronomical discoveries for rapid follow-up satellite observations, and

c. monitoring and optimizing the onboard processing program.

This quick look data stream extracts bright point sources from the data base. A chronologically ordered list of source detections, with focal plane redundancies removed, is combined with aspect

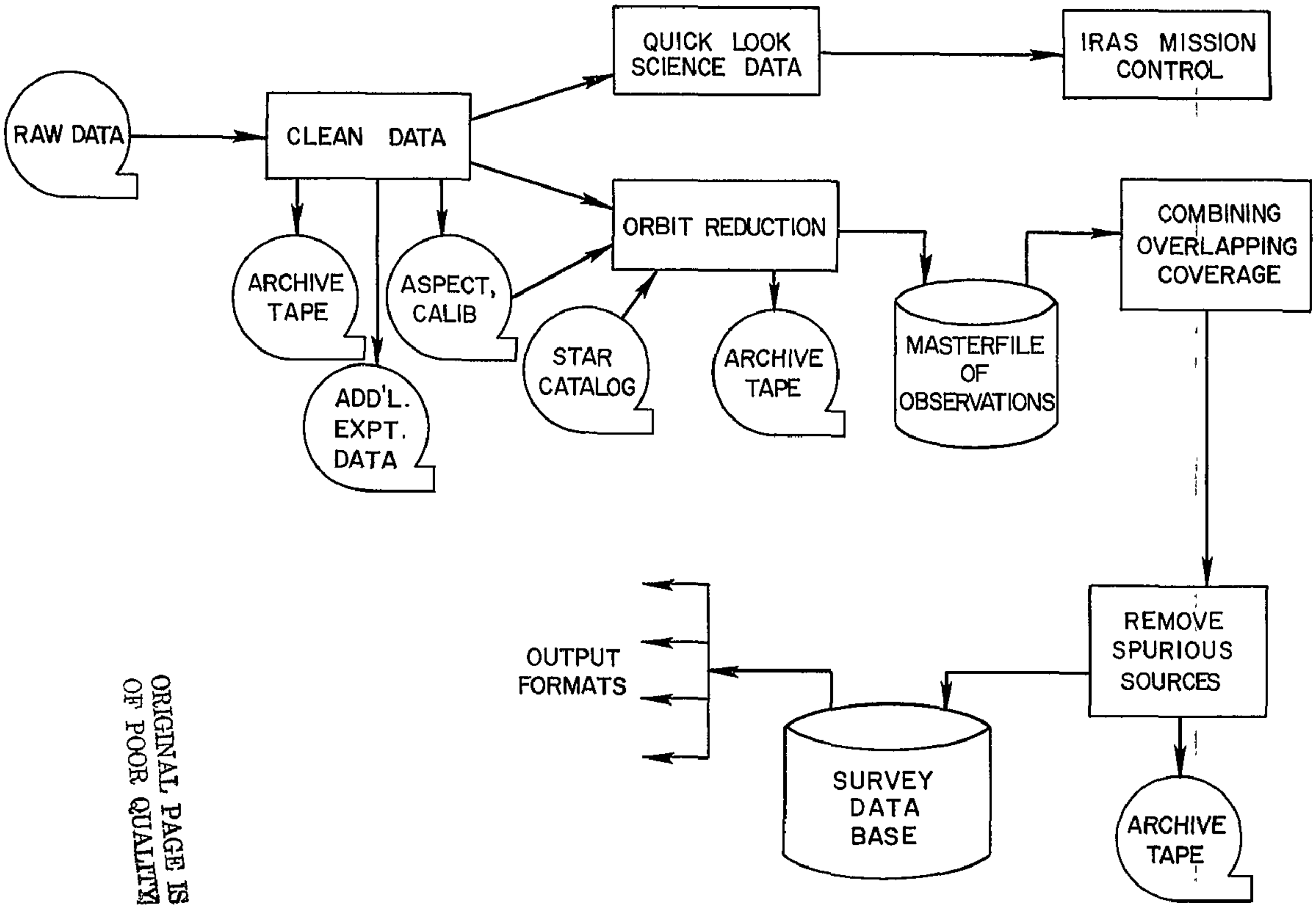

Figure 4.5. Iras Data Reduction and Analysis

information to produce a list of Quick Look Sources in celestial coordinates. These data must be accessible to the IRAS control center within 2 weeks for effective use. This task could be performed by any reasonable minicomputer or time shared larger system.

The second processing path takes the data processing through the final survey outputs. The first step is the orbit reduction. This step might possibly be done on a mini computer, but can certainly be accomplished on a full scale computer. (It might be possible for micro processors to provide much of this processing, at least through single channel operations.) A more detailed discussion of this question is contained in the feasibility assessment.

The master file of observations, containing all observations of the survey, will be the heart of the data base. The organization of all the data in this file will determine the rest of the data processing, and must be designed carefully for maximum efficiency of subsequent access. The storage required of this file seems to require a large-scale computer for further processing, but the mini system is not completely ruled out at this point. Periodically, the new additions to the master file will be combined into one master data base. Multiple sightings of sources will be combined, preserving observational histories. Sources failing the consecutive orbit confirmation criterion will be removed. Solar system objects will be flagged. This file will become the master data base from which all outputs are generated. During the survey, outputs from the master file will be used to monitor the quality of the data.

The choice of output formats will determine how effectively the results of the survey are used. Several "standard outputs" have

been identified as being most effective in communicating the survey results to the general astronomical community. These formats are:

1. A printed catalog of the "most interesting" sources found in the survey. This will provide a representative sample of all the important classes of infrared sources from the survey. To be effectively used, this catalog will contain all relevant information (observations, identifications, etc.) on 10,000 - 30,000 sources, and so will contain a minor fraction (3% at best) of the survey data. This catalog should receive wide distribution to individual astronomers.

2. A complete catalog of all point-like sources found in the survey. This catalog (containing 10^6 - 10^7 sources) would be written on 5 - 10 computer-compatible magnetic tapes (depending on the information included and tape format). It is anticipated that all major astrophysics research groups could acquire this catalog for specific research projects and as a fundamental reference catalog.

3. A set of transparancies (on the scale of the Palomar/ESO/SRC Schmidt surveys) presenting the full survey catalog as overlays for the Palomar Sky Survey. This form is intended to allow maximum visual comprehension of the enormous survey data base. In this form, comparisons of the infrared and visual skies can be made by astronomers without developing the complex computer programs necessary to use the magnetic tapes. In addition, positions will be accurate enough, and intensities coded, to allow a good fraction of the information content of the survey to be obtained from the transparencies. It is anticipated that major astrophysical research groups and libraries would be likely subscribers to this output format. In addition to the "standard outputs" the full survey data base could be made available to all astronomers for more specialized output requirements as the resources of the project permit.

9. CALIBRATION

The calibration of the telescope system will be accomplished primarily through the observations of known stars. With a dynamic range of 10^5, several thousands of the brightest sources found on the survey will be accessible to careful observations by ground-based, airborne and balloon telescopes. These will provide reliable calibrations of the system as a whole and avoid the expensive, less reliable, preflight full photometric calibrations.

V. MISSION AND SPACECRAFT DESCRIPTION

MISSION DESCRIPTION

The selected IRAS orbit is a circular sunsynchronous twilight orbit with the following parameters:

altitude	:	900 km
period	:	103 minutes
inclination	:	99°

This orbit was chosen as the best compromise between radiation background, contamination by the earth's atmosphere, data transmission requirements, duration of ground contact, eclipse duration and launch vehicle capabilities.

The launch vehicle is the Thor Delta 2910 and the launch site will be the Western Test Range in California.

For the execution of the survey use is made of the scan mode of the satellite. During the scan, the satellite is rotated with a constant angular velocity around the sun vector in the direction of the orbital velocity. During this motion, the angle between the Sun vector and the experiment axis is kept constant. In this way a circular band of the celestial sphere is observed, of which the width is equal to the instrument field of view. The viewing direction can be varied within the following two constraints. The viewing angle relative to the Sun should have a value between 60° and 120°. Furthermore the viewing angle relative to the local vertical is nominally limited to $\pm 30^{\circ}$.

The percentage of the sky covered as a function of time is determined by:

- the limitations in viewing direction
- the starting date of the survey and consequently the launch date
- the survey detector array width
- the survey method.

In case of the above mentioned limitations for the viewing direction and a detector array width of 30 arcmin., the sky coverage as a function of time over a period of half a year is as shown in fig. 5.1.

The starting time and survey method have been optimized for maximum initial sky coverage.

Repetition of the survey on the time scale of hours is obtained by stepping the viewing direction of the satellite in a suitable way such as giving it an offset of half the detector array width per orbit. The precise method to be adopted will depend on the need to avoid the particle radiation interference of the South Atlantic Anomaly.

The 20 days repetition will be produced by going through the full viewing angle range and by repeating this every three weeks. In case of the nominal values for this range and the 30 arc min array width, this results in the pattern as indicated in fig. 5.2. for objects in the ecliptic. This repetition pattern is only applicable in case there are no extraneous disturbances on the measurement caused, for example, by particle radiation and Moon interference.

After 4 to 5 months the survey of the whole celestial sphere will have been completed and can be repeated once more. The loss of

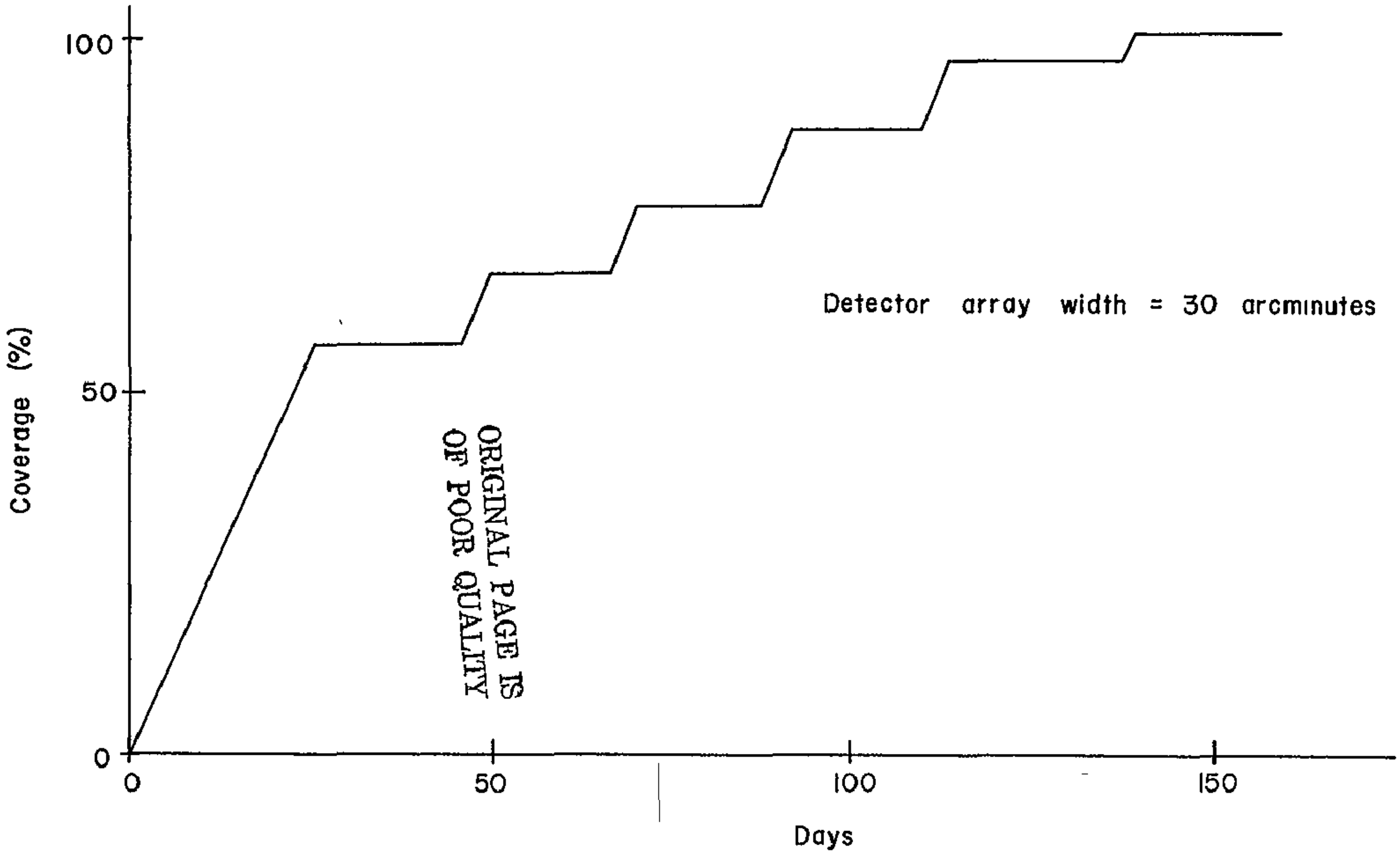

Fig 5 1 Sky coverage vs time for the survey.

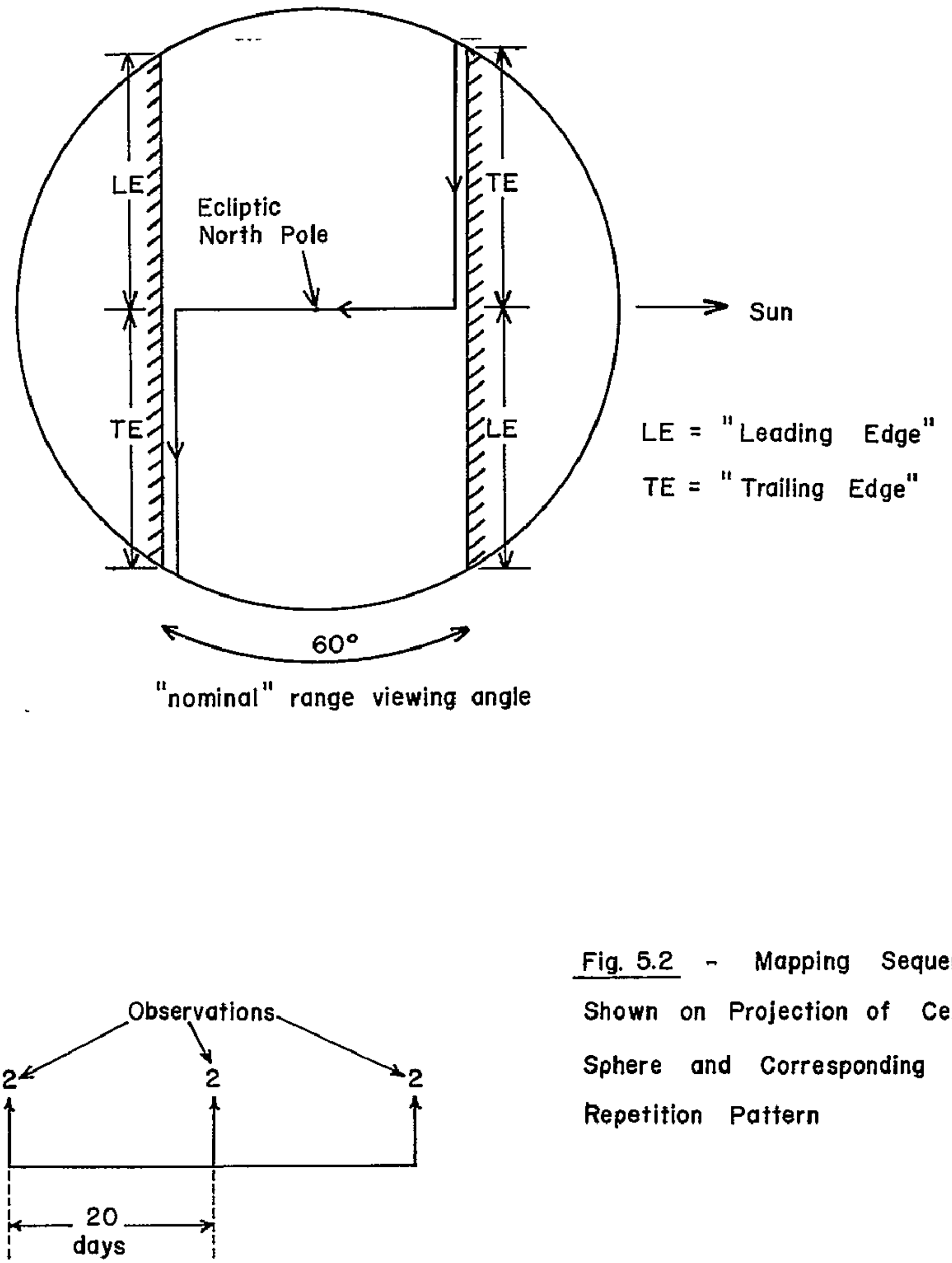

Fig. 5.2 - Mapping Sequence Shown on Projection of Celestial Sphere and Corresponding Repetition Pattern

observation time due to the Moon depends on the allowable angle between the Moon and the experiment axis. Even if this angle is 30^{o}, the potential loss would be less than 10%. This loss can be reduced to virtually zero by proper scheduling, but at the expense of the regularity in the repetition pattern.

Apart from the continuous scan in one direction it is possible to perform a raster scan over a small area of the sky. The time available for such a raster scan is about 15 minutes. Scan speeds can vary between 2 and 10 arc munutes sec^{-1}. The IRAS will be capable of pointing, under gyro control, in a predetermined direction. The maximum duration of a pointed observation is about 15 minutes. Accuracy of pointing direction will be better than 2 arcminutes.

Spacecraft configuration

The spacecraft portion of the IRAS satellite consists of a slightly conical outer structure, which is mated to the launch vehicle adapter and the infrared experiment. In this structure a horizontal honeycomb platform is incorporated to which most of the equipment is mounted. Some attitude sensors and the battery are attached to the outside of the cone.

Power is generated by two deployable solar panels. A secondary purpose of the panels is to shield the dewar from the sun. The main antenna is mounted at the bottom of the satellite, while an antenna with lower gain is attached to the experiment. In this way omnidirectional coverage is achieved. Thermal control is obtained passively by using super insulation and suitable coatings at appropriate locations. A general view of a possible configuration for IRAS is given in fig. 5.3., while a cross section of the spacecraft is shown in fig. 5.4.

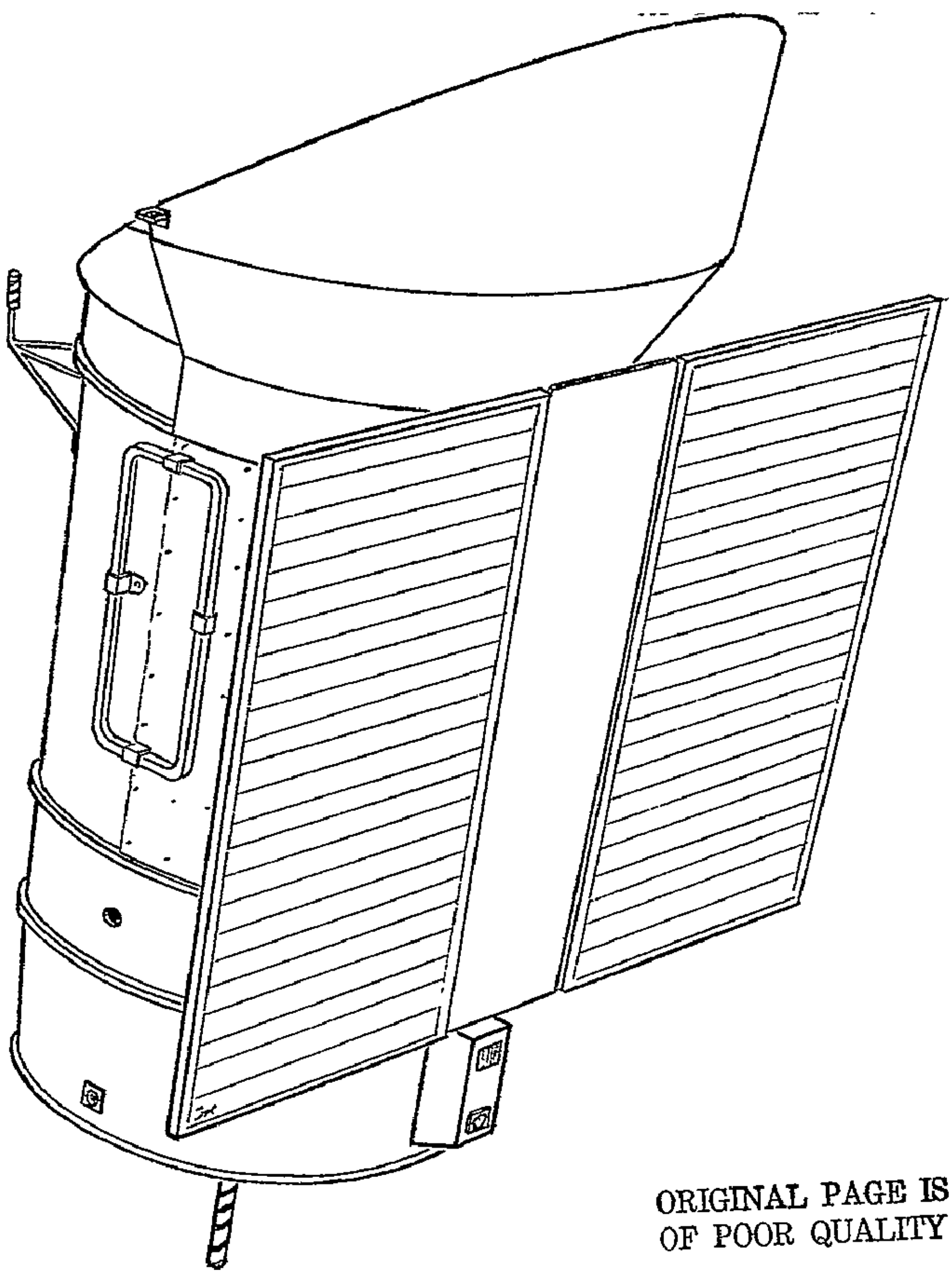

Fig. 5.3. POSSIBLE CONFIGURATION FOR IRAS

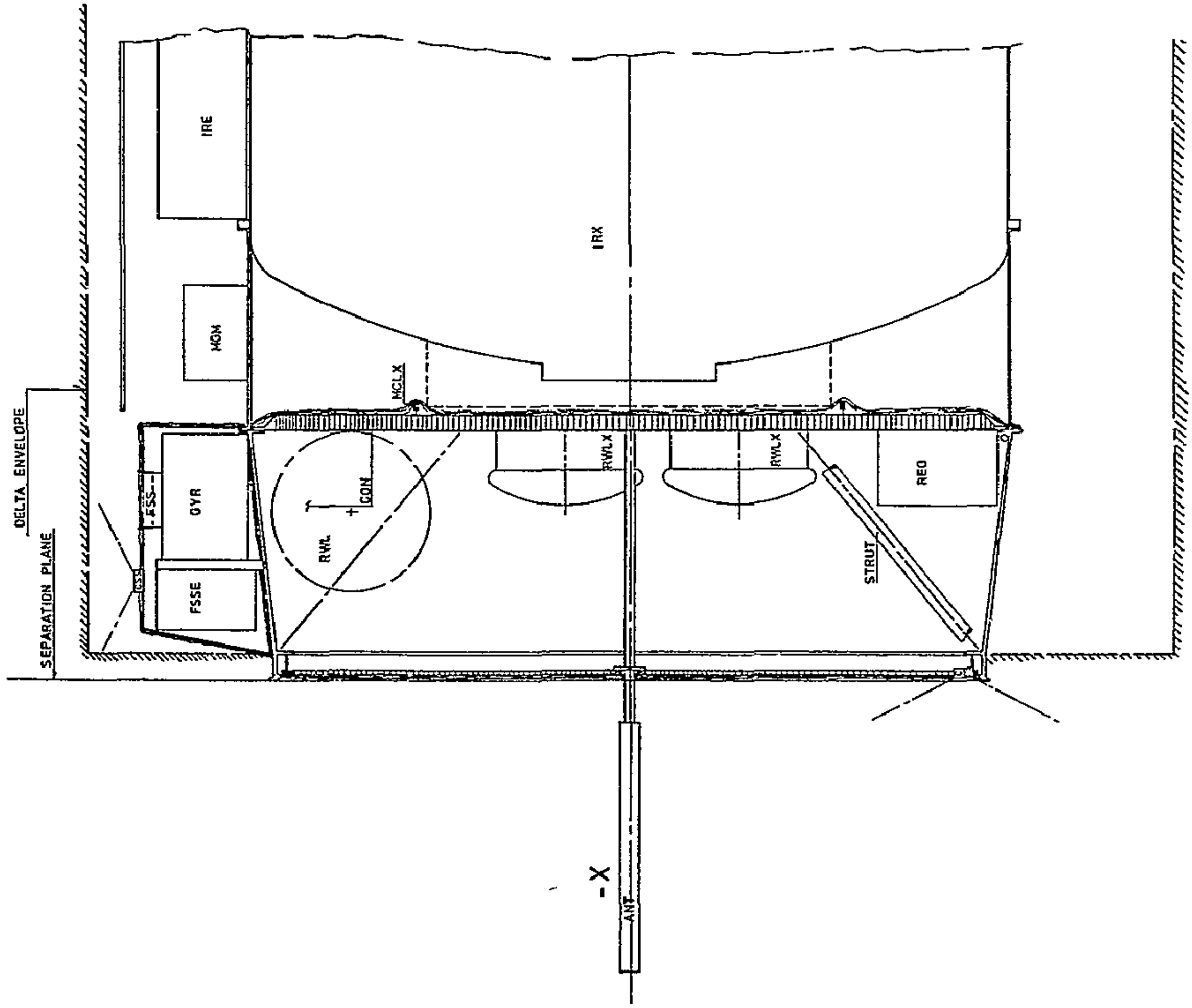

Fig. 5.4. <u>LAYOUT SPACECRAFT UNITS SIDE VIEW</u>

The attitude control subsystem uses the Sun and stars as prime attitude references. In principle the angle between the experiment axis and the Sun will be held constant for one half orbit, while the motion around the Sun vector will be executed under gyro control. Absolute reference information will be obtained by means of visual sensors in the telescope. The algorithms for the attitude control are contained in the on-board computer program memory. Reaction wheels serve as the prime actuators and are unloaded using magnetic coils. During eclipses and sun acquisition a three axis gyropackage provides the necessary attitude and rate information.

The estimated accuracies using the visible light detectors in the focal plane are better than ±0.3 arcminutes absolute around all three axes. The short term stability (limit cycle) will be better than ±10 arcseconds. All the above numbers are 2 sigma values and pertain to the reconstituted attitude of the experiment axis.

Two different memories for data storage are provided: a mechanically redundant tape recorder and a solid state memory. The data coming from the experiment are stored on the recorder via one of the two available on-board processors. Attitude and housekeeping data necessary for ground processing are added. The capacity of the recorder is 4.5×10^8 bits.

The solid state memory contains the programs for the execution of attitude control and experiment and housekeeping data handling. It is also used for storage of experiment performance information and housekeeping data. Total capacity is 64,000 16 bit words.

The stored data are transmitted to the ground with a bit rate of 0.75 Mbps during the ground contact of about 12 minutes. Apart from this, housekeeping data are telemetered continuously to the ground with a bit rate of 2 Kbps.

Experiment Interface

Many interfaces between the experiment and the spacecraft obviously exist. Only some major constraints imposed by the spacecraft are mentioned below.

- Configuration

Obviously the dimensions of IRAS have to fit within the Thor Delta heat shield. Furthermore the total mass at lift-off should not exceed 1066 kg. To satisfy the attitude control performance it is required that the total satellite moments of inertia comply with the following limits:

- Moments of inertia not to exceed 700 kg m^2
- Difference in moments of inertia not to exceed 250 kg m^2
- Products of inertia not to exceed 8 kg m^2 or 2 percent of minimum moment of inertia.

- Data stream

The tape recorder capacity limits the number of bits to 3×10^8 bits per dump.

- Power

Two supply voltages are available, 28 and 5 Volts. The power presently allotted to the experiment is 15 Watts from the 28V and 5 Watts from the 5V supply.

- Viewing angles

The spacecraft will allow viewing angles relative to the Sun from 60^{o} to 120^{o}.

OPERATIONS

It is foreseen that the operations will be executed from the control center of the Appleton Laboratory in Slough, UK with a ground station situated near Chilbolton, U.K., while NASA ground stations will provide back-up, emergency and in-orbit check-out support. Once every 12 hours an instruction list defining the observations to be executed during the following 12 hours period will be sent to the satellite. During the same ground contact the data accumulated during the previous 12 hours will be telemetered to the ground.

VI. ANALYSIS OF POTENTIAL TECHNICAL PROBLEMS

In the following sections we address in some depth technical problems which at the start of the study seemed of special difficulty and importance. A summary of a study of the AFCRL rocket survey is included since that survey is a close predecessor of the proposed survey.

1. SENSITIVITY TO CHARGED PARTICLES

High sensitivity infrared detectors are also sensitive detectors of energetic particles. Cosmic rays and trapped particles are therefore a potential noise source for an infrared astronomical satellite. By moderate shielding of the detectors and by using pulse suppression electronics, the effects of ionizing particles can be kept to an acceptable minimum over nearly all of the satellite's orbit. High energy protons ($E > 100$ MeV) will degrade the sattelite's performance close to the center of the South Atlantic Anomaly. The system will be seriously affected about 5% of the total flight time.

In the following sections the behaviour of infrared detectors will be outlined in terms of their response to charged particles. Representative values of the external radiation field and the shielding properties of the satellite will be given. In addition, the problems of activation of the satellite by cosmic rays, the probability of large solar bursts during the satellite's year of operation and the likelihood of permanent damage from radiation will be briefly considered. None of these three is a serious threat to the successful completion of the survey.

Infrared Detectors as Particle Detectors

Both bolometers and photoconductive infrared detectors respond to charged particles. The analysis of bolometric devices is particularly simple since the particles' energy loss is converted to heat and from there on produces the same output as an equivalent short burst of infrared energy. The bolometer temperature rises in less than a millisecond and falls with the time constant of the bolometer. Feedback circuits can be used to reduce this time constant; thus deglitching circuits can be used. However, it is important to reduce the radiation effects which have to be removed to a minimum by shielding and reduction of the detector size.

Photoconductors respond to particles much like conventional proportional counters. The number of hole electron pairs produced by the passage of a charged particle is given by:

$$N_{pulse} = \frac{\Delta E_{CP}}{3E_g}$$

where E_g is the intrinsic energy gap (for Si, $E_g = 1.12$ eV; for Ge, $E_g = 0.67$ eV). ΔE_{CP} is the energy lost by the charged particle. The rms fluctuations in the free carrier generation due to background fluctuations is:

$$N_{rms} \approx \sqrt{\eta \frac{P_b}{h\nu} \Delta t}$$

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where η is the quantum efficiency, P_b is the incident background power, $h\nu$ is the photon energy and Δt is the integration time. As an example, for the 10 μm survey detectors,

$$N_{rms} \sim \sqrt{2 \times 10^7 \Delta t} \; ;$$

thus the ratio of the number of free carriers produced by particle ionization to the rms uncertainty in the number of free carriers produced by the background photon flux in the 10 μ channel is:

$$\frac{N_{pulse}}{N_{rms}} \approx \frac{\Delta E_{cp}}{1.5 \times 10^4 \, E_g \, \sqrt{\Delta t}} \; .$$

For a sampling rate of 8/sec ($\Delta t \sim 0.12$ sec) the pulse produced by a particle which loses 1 Mev in the detector will be ∿200 x the rms noise level.

Rise time and pulse heights for charged particles events depend on electronic bandwidth. Because the intrinsic response speed of photoconductors is very fast ($\lesssim 10^{-6}$ seconds), there is great potential for discriminating between infrared sources and charged particles. In practice the very high resistance of photoconductive detectors limits the tolerable rate of particle events. Estimates of the acceptable rate for charged particle events range from 30 to 300 sec^{-1}. The variation depends on the amounts of power, weight and space that are available for the signal processing electronics. The value of 30 sec^{-1} is conservative and will be used in the following discussion. A detector size of 1 x 1 x 1 mm^3 will also be assumed.

The charged particle environment and the shielding properties of the telescope

NASA (NSSDC reports 72-11 and 74-03) has constructed detailed tables of the near Earth electron and proton environments. The majority of the protons have energies less than 100 MeV and their shield penetration can be treated by simple range energy methods. A small number of neutrons are produced by occasional nuclear reactions, but they are too few to be a serious problem.

Trapped electrons are quickly stopped by the outer skin of the spacecraft/telescope (all stop in ≈ 1 cm of Al). However, a significant fraction, F, of the total electron input energy is converted into bremsstrahlung, where

$$F = .005 \left(\frac{Z}{13}\right) E_e .$$

Z is the atomic number of the stopping material, E_e is the electrons initial energy in MeV. Approximately 75% of the γ's have energies E_γ of 0.1 to 0.5 MeV. In order to prevent these secondaries from reaching the detector it is desirable to surround the detectors with a high Z material to stop the γ's. Four shielding geometries have been analyzed using NASA's charged particle code, CHARGE. (Charge Code for Space Radiation Shielding Analysis, W. R. Yucker and J. R. Lilley, McDonald Douglas Corp. DAC-62231, April 1969.)

Case	Shield
1	1 cm Al (2.7 gm/cm^2)
2	2 cm Al (5.4 gm/cm^2)

Case	Shield
3	1 cm Al (2.7 gm/cm^2) + 1 cm Cu (8.9 gm/cm^2)
4	1 cm Al (2.7 gm/cm^2) + 1 cm Pb (11.3 gm/cm^2)

The input particle spectra are shown in figs. 6.1 and 6.2. Cases 1 and 4 have been analyzed by hand with nearly (within 2 x) the same results as for the CHARGE program. The results of this analysis are shown in table 6.1. Even for case 4 the counting rate (mostly protons) exceeds the assumed limit of 30 sec^{-1} at the peak (in the center of the South Atlantic Anomaly). Figure 6.3 shows, for case 4, how much the counting rates are decreased if a fraction of the orbit (long term average) is dropped from the observing program. For example, if data are not taken over 5% of the average orbit the maximum proton counting rate is cut by a factor of 3, which in shielding case 4 reduces the peak counting rate to 30 sec^{-1}. The electron curve in figure 6.3 is very conservative since the data for compiling the figure included high energy electrons from previous high altitude nuclear tests. These electrons are no longer present and have not been included in the rate analysis. Contour maps free of the fission fragment electrons are not yet available.

Cosmic Rays

Well away from the South Atlantic Anomaly, the counting rate will be determined by primary cosmic rays and their secondaries. The resultant counting rate is predicted to be <1 sec^{-1} for each detector (1 x 1 x 1 mm). This estimate includes a factor of 2 for secondaries produced in the spacecraft. Other experiments have experienced enhancements of this size.

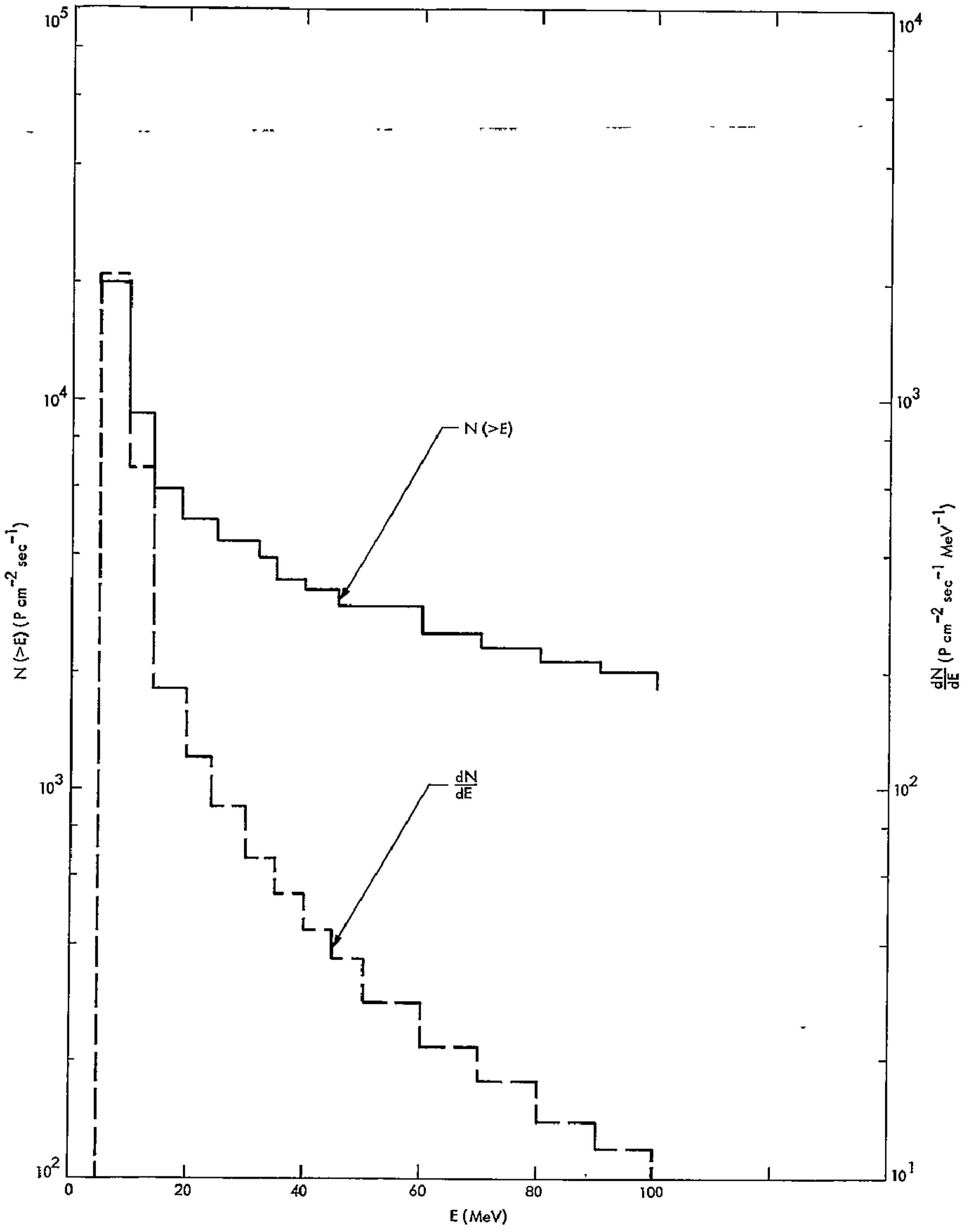

Figure 6.1. Ambient Proton Spectrum, Worst Case

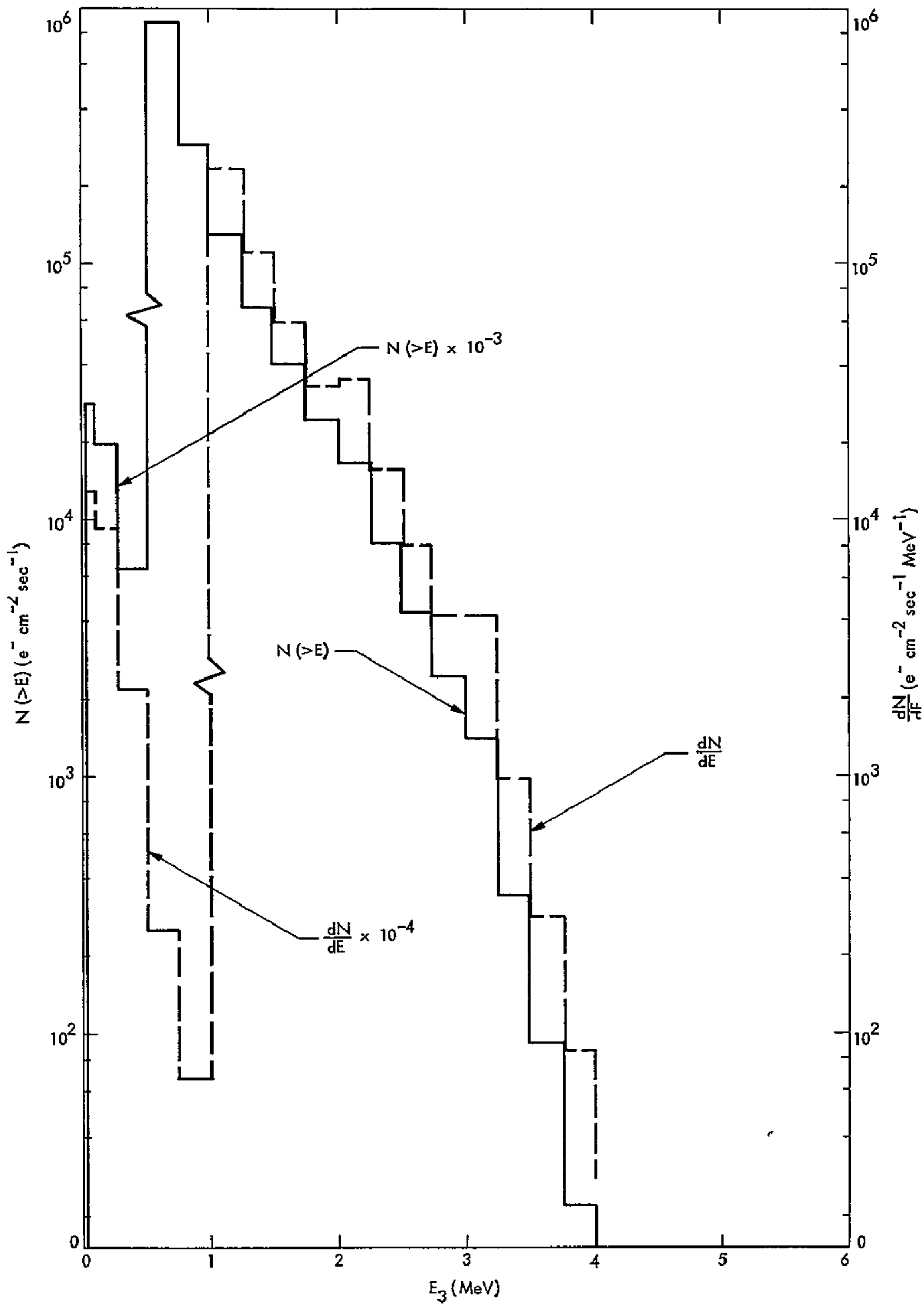

Figure 6.2 Ambient Electron Spectrum

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Case	Transmitted Protons $(cm^{-2} sec^{-1})$	Proton Counts (sec^{-1})	Transmitted γ's $(cm^{-2} sec^{-1})$	E_γ (MeV)	Counts		Total Counts	
					(Si) (sec^{-1})	(Ge) (sec^{-1})	(Si) (sec^{-1})	(Ge) (sec^{-1})
1	3×10^3	180	2×10^5	0.05	2.7×10^4	6×10^4	2.7×10^4	6×10^4
2	2.5×10^3	150	1.4×10^5	0.06	3.8×10^3	8.4×10^3	4×10^3	8.6×10^3
3	1.8×10^3	110	1.1×10^4	.15	1.7×10^2	4.2×10^2	280	530
4	1.6×10^3	96	4.8×10^2	0.5	5.2	9.5	101	106

Table 6.1. - Radiation Hit Analysis for Four Shielding Geometries

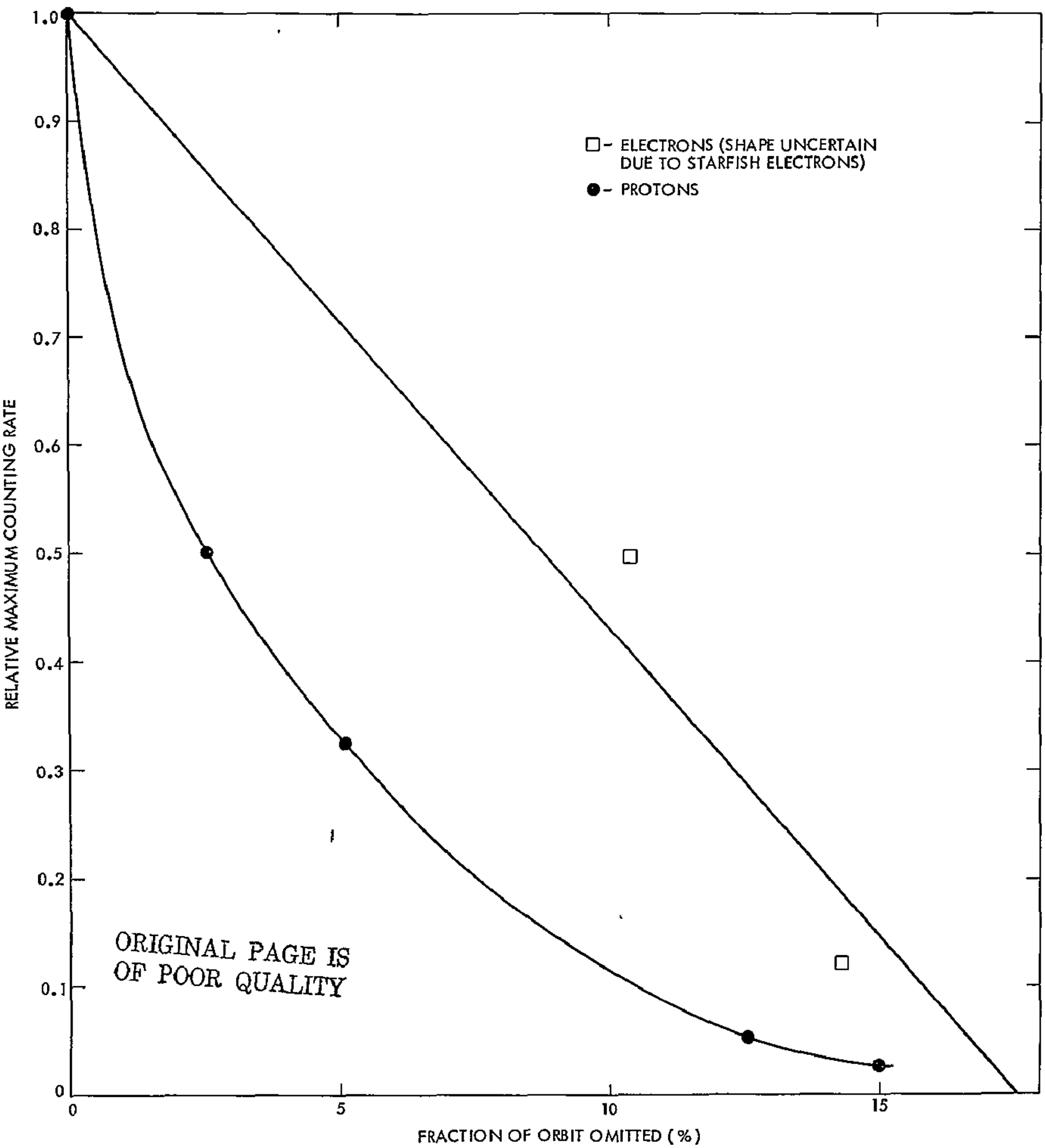


Figure 6.3 Relative Counting Rates if Fraction of Orbit is Deleted from Observing Program

Satellite Activation

Several materials are susceptible to activation by the incident charged particle flux; the most troublesome are thorium, potassium, and uranium. These materials should not be used in the immediate vicinity of the detectors.

Permanent Detector Damage

Measurements indicate that high sensitivity silicon detectors suffer permanent damage for total radiation exposures of 10^5 Rad (North American Rockwell, 1976). For the assumed 1 x 1 x 1 mm^3 detector this corresponds to 3 x 10^{10} protons (about 3 x $10^{12}\gamma$'s). The total average daily exposure is approximately 10^6 protons/day. This gives a useful life of 10^4 days, well in excess of the mission lifetime.

Solar Flares

The prediction of solar flare events is of course impossible, but one can make estimates on the basis of the data of previous years (J. H. King, J. Spacecraft (1974) II, 401). Typical large solar flares result in peak proton fluxes ($E > 100$ MeV) of 10^2 cm^{-2} sec^{-1}. Flares of this magnitude last for 1-3 days with total particle numbers of 10^7 cm^{-2}. The probability of exceeding 10^3 protons/second during a solar flare is predicted to be 25% for a one year mission in the early 1980's. If such an event does occur, it will probably overload the pulse rejection electronics for a period of about 1 day.

2. CRYO-CONTAMINATION

Contamination to LHe cooled optical surfaces and detector elements can be limited to levels that will not appreciably affect the system response.

To achieve this, the minimum orbital altitude of 900 km has been chosen together with limitations to the spacecraft manoeuvers. The aperture to the telescope cavity should not be pointed into the velocity vector for extended periods of time. It is advisable that the velocity shadow be limited to a penetration depth inside the telescope tube of one aperture radius at any time. The ejection cover should be used as a cryo pump and should not be ejected until about two weeks after launch. Two weeks is estimated as necessary for sufficient outgassing of all exposed satellite surfaces and components.

Data contamination due to response to dust particles and other debris associated with the satellite have not been considered in detail for this report. This problem can be serious and will require further study. It is generally recognized that an instrument of this sensitivity covering wavelengths from 8 to 120 m will be very susceptible to dust contamination due to emission from or scattering off of debris surrounding the spacecraft. Careful attention to materials selection, fabrication techniques, cleanroom facilities and payload conditions will be necessary to manage this source of contamination.

The SIRTF study has concluded that problems arising from dust contamination can be avoided by careful cleaning procedures. This finding has been confirmed by high sensitivity sounding rocket experiments.

3. DATA PROCESSING

The problems in analyzing the data processing for IRAS are created by the large data volume of 5×10^8 bits/day. The raw data stream from IRAS must be processed effectively and great care must be taken to insure that this is done for a manageable cost.

The initial cleaning and formating of the data is most appropriately handled by NASA which routinely provides this service for much higher data rates. The quick-look data processing step is likewise straightforward, and presents no technical problems. The potential problems in this step are due to the pressure of the necessary rapid turnaround time for useful interaction with the satellite operations. This will require careful logistic planning to guarantee that time is not lost in transferring data from Europe to the processing center. The quick-look data should be processed at the same place where the spacecraft-tape-dump is cleaned to minimize delays in processing. It may be necessary to establish a low speed data communication line between the data processing center and the IRAS mission control.

An alternative method of generating the quick-look data is to use the satellite onboard computer and interleave the raw data and processed data onto the tape recorder. A hardwired decommutator would then extract the processed data and generate a separate tape each time the tape recorder data is dumped. The quick-look processing could then be done at the mission control center, eliminating the pressure of rapid turnaround for the entire mission of the quick-look data at the data processing center. This would also reduce the cost of the data processing. In any event the ground processing must have rapid turnaround in the initial satellite operations to allow rapid optimization of the onboard processing algorithms. The feasibility of this approach must be investigated.

The orbit reduction step presents a considerable processing task. Two alternative possibilities are a devoted mini-computer system and a time shared large computer. The minicomputers currently available are large and quite fast. A minicomputer can do an add operation in 2 μsec, while a powerful large scale computer can do an add operation in 0.3 μsec. Therefore a minicomputer system running for 24 hours/day is nominally equivalent to the use of a large scale computer for 3.5 hrs/day. With a 6×10^7 words/day data rate (5×10^8 bits, 8 bit words) this would allow 600 add operations per data word using a devoted mini system or an equivalent amount of large computer time. It is difficult to assess how realistic this figure is for IRAS data processing. Two independent estimates suggest this may not be enough time to process the data. The CRL High Star program used the time equivalent to 1300 adds/data word to process their data. The data processing on the Atmospheric Explorer series is also equivalent to 1300 adds/ data word. These suggest that the number of operations available per data word may be insufficient. If so, two alternatives are immediately apparent. First, multiple CPU's can operate on the same core memory in a mini system. Alternatively, buying larger amounts of large scale computer time could make it cost effective to lease a devoted system for the lifetime of IRAS, allowing the entire processing to be done by a single large machine.

The master file of observations will require a large storage capability, and this will present a problem for any computer system. If we preserve all observations of the entire sky in 1' square bins (1.5×10^8 bins) and use 200 bits/bin to describe all observations of a given area, then the mass storage requirement of IRAS is 3×10^{10} bits.

The maximum on-line storage of a minicomputer disk system is 7×10^9 bits (eight disk packs) so that we cannot have the entire data base available on a random access basis. The most cost

effective mass memory on a large scale computer is the IBM 3850 mass storage system. This sytem has a random access memory of $\geq 3 \times 10^{11}$ bits and appears to meet the IRAS storage requirements for all processing needs including co-adding of all survey data.

If we eliminate the requirement of storing all information for the entire sky, and only store information on positive source detections, the storage requirement is reduced to 2×10^9 bits (10^7 sources, 200 bits/source). Either a mini system or a large computer could handle the storage. In this case, data organization becomes a much more difficult problem, and requires careful planning for maximum efficiency of later data extraction (for combining multiple sightings, etc.).

The major result of the feasibility assessment of the data processing is that it can be done, but careful trade-off analysis is needed to devise the optimum processing system. Once the focal plane design has been established, algorithms for processing (both onboard and ground processing) should be written and comparisons of different possible systems made to establish the most effective means of processing the data.

The cost of creating the final survey outputs could be significant and must be considered in the project cost. Certainly the project must bear the cost of producing master copies of all standard output forms. Producing large numbers of copies of different outputs might be costly, and could be partially borne by those subscribing to the outputs. The non-negligible costs of magnetic tapes and transparencies might require the subscribers to these output forms to pay at least the material costs. The tape version of the catalog would be 10 tapes at $10-15 each, transparency overlays on the scale of the Palomar Sky Survey would require at least 1200 14 inch x 14 inch (36 cm x 36 cm) overlays. At $1 each, the cost of transparencies is already large.

Finally, the question of access to the master file by non-project astronomers must be considered in developing the data system. If this is considered in the data processing, it will involve additional cost (documentation, user oriented programmers, etc.). Since this file is really of significant value to all astronomers it might be considered that the master data file be made available through national observatories.

4. CRYOGENICS

We have considered three cryogenic systems

A. A pure superfluid system

B. A supercritical system plus a Joule-Thomson expansion valve

C. A hybrid system consisting of a superfluid and a supercritical system.

We believe that both (A) and (C) will satisfy all the IRAS requirements. Option (B) has been rejected because of potential lack of temperature stability, efficiency and reliability. Option (C) is favored on the basis that some possible problems of (A) which are still untested are avoided, but the final choice between options (A) and (C) will depend on a more detailed engineering study which takes into account cost, reliability and performance.

A. Superfluid System

On the basis of the work carried out in this study we can state that the IRAS cryogenic requirements could be met by a large superfluid system of the type developed by Ball Brothers Research Corporation. (See IRAS, Concept Description, December 1975 and Final Report from BBRC to Goddard (E. Hymowitz)).

One of the problems posed by a very large superfluid dewar is the fact that as liquid is consumed the two fluid phases will permit "sloshing" and the center of gravity will move in response to acceleration. Calculations have been carried out to show that neither of these effects could pose serious difficulties for the IRAS attitude control system. It has been suggested, however, that interior baffles within the helium vessel would be useful to restrict circular motions of the fluid. Obviously these problems, if they exist, are more serious as the volume and size of the dewar is increased. Although experiments have not yet been conducted to fully document the behaviour of superfluid helium in zero gravity there are no known phenomena which should significantly degrade the performance of such a system.

B. Super-Critical System

As part of the Hughes Aircraft Company baseline study carried out during this project, alternative cryogenic systems were studied. It is possible to meet most the IRAS cryogenic requirements by means of a large low pressure supercritical helium storage system of the type used successfully on the Apollo program. In the supercritical state, the helium is stored at temperatures which vary from 5.2K to more than 7K. Some work has been carried out by NASA on the development of a Joule-Thomson expansion system which would convert a portion of the pressurized supercritical helium into a small, continuous supply of superfluid at 2K. Because this system is complex and potentially unstable, it has been rejected as a solution for this mission.

C. The Hybrid System

A hybrid system in which the low power, low temperature requirement is met by a relatively small quantity of superfluid which is then combined with a larger amount of supercritical helium to provide the bulk of the cooling at higher temperatures was found to be attractive. Systems of this type can be designed for a variety of heat loads and temperatures with great flexibility, reliability and redundancy. Concern over the two-fluid instability problem in a large superfluid system is reduced. In particular, since liquid storage in large containers may present problems under zero gravity condition, it is attractive to consider storage in the single phase supercritical state. The 3 atm., 5.2K supercritical tank studied by Hughes Aircraft Company is efficient, and appears to offer both simplicity and reliability in its design and operation. The problem of stratification may be overcome by including a high thermal conductivity matrix inside the tank. Helium in the 3 atm supercritical state is 30% less dense than helium in its liquid state. Thus the hybrid system suffers a 30% penalty in density but in return avoids worries over "sloshing," motion of the center of gravity, etc.

In finally deciding between the hybrid and the pure superfluid systems it is important to understand the heat loads of the three low temperature domains: 10 mW at 3K, 5-15 mW at 10K and 50 mW at 16 K. Liquid helium is needed to supply the lowest temperature for the detectors, but its latent heat is only 23 J/g. This clearly indicates that most of the cooling should be provided by the large enthalpy change of He vapor as it warms from 2 to 16K (71 J/g) or by a supercritical tank and associated heat exchanger where the supercritical tank provides 22 J/g of cooling and the evolving gas takes up 61 J/g in warming to 16K. Thus either form of helium can be used with nearly equal cryogenic efficiency. Table 6.2. shows the cooling capacity of several different systems. For comparison

	Superfluid	Supercritical			
	2K	5.2-6.5K	5.2-8K	5.2-12K	5.2-16K
Tank	23	13	18	21	22
Heat Exchanger	71	50	56	58	61
Total	94	63	74	79	83

Table 6.2. - Average Cooling Capacity in Joules/g for Superfluid Helium and 3 atm. Supercritical Helium Systems

the superfluid case is included where the evolving gas and the boiling liquid are both used to cool the baffle and shield. In the four examples of supercritical systems it can be seen that the total cooling capacity, as well as the amount of cooling provided by the tank relative to that provided by the evolving gas, varies as a function of the final tank temperature. Furthermore, in an unregulated system operated at constant pressure the cooling capacity varies considerably. In practice it may be difficult to achieve the full thermodynamic limit of performance illustrated in Table 6.2. However, the cost of achieving the highest performance will heed to be compared to the cost of increasing the capacity or decreasing the heat loads through more efficient designs.

There are three other points which favor the hybrid system over a pure superfluid system. First, if one part fails the other will continue to provide cooling for some time. Second, at least the supercritical part can be fully tested under normal gravity. Third, both parts can be individually optimized as the overall design is optimized.

The present design represents a substantial reduction in cryogen from the design presented in "IRAS, Concept Description (1975)" which requires 100 kg liquid helium. In particular, an effort was made to reduce the amount of cryogen needed in order to reduce size and weight and the risks associated with large cryogenic vessels. This is now possible since the experiment load has been reduced from 50 mW to 10 mW and the telescope baffle temperature has been increased to 16K. In the present design the 3K load is carried by 13 kg of superfluid; the 37 kg of supercritical helium carries 50 mW of parasitic load and the brunt of the aperture load. 30 mW now comes from the launch supports; further design effort should cut this in half. The optics do not present a cooling load directly but are "over-cooled" by the helium gas evolving from the superfluid tank.

In summary, the baseline hybrid concept described in chapter IV is based on well established cryogenic techniques and procedures. It is a flexible design which falls well within the size and weight restrictions imposed by the spacecraft. Thus, it can easily be adjusted if additional cryogenic requirements are encountered in later phases of the design. By the same token, if more efficient methods are found for supporting the system during launch or if the experiment dissipation is reduced, for example by reducing the number of detectors, adjustments can easily be made in either or both parts of the system. Thus, not only for missions similar to IRAS, but for other long duration missions involving low temperatures, it is felt that systems of this type may find wide application. It is gratifying to note that at the outset of this study, the cryogenic problem loomed as perhaps our greatest concern. Now we are convinced that there is more than one acceptable solution to this problem and we are confident that we have learned enough to choose the best of these solutions.

5. DETECTORS

The IRAS experiment is now possible because of recent development of extrinsic photoconductive detectors which have very high sensitivity under low background conditions. Table 4.6 lists the properties of the detectors selected for use in the conceptual design together with the background limited Noise Equivalent Power (NEP) expected for these detectors in the IRAS satellite. The last column gives the frequency range of operation in the survey mode.

8-15 μm Si:As

Arsenic doped silicon detectors are the most highly developed of the extrinsic photoconductors. The parameters listed in table 4.6 have been determined under low-background conditions and, as shown in Section IV, detectors with these characteristics should be background photon noise limited on IRAS. In order that thermal generation of free carriers be negligible these detectors are operated at temperatures $\lesssim$14K.

15-30 μm Si:Sb

Although antimony doped silicon detectors have received less attention that Si:As in recent years, a substantial developmental effort has been applied to this material. The properties shown in table 4.6 are determined under low background conditions and detectors with these characteristics should be background photon noise limited on IRAS. In order that thermal generation of free carriers be negligible, these detectors are operated at temperatures $\lesssim$12K.

30-60 μm Ge:Be

A Beryllium doped Germanium detector was selected for the 30-60 μm channel because of its well placed cut-off wavelength. Very little is known about Ge:Be detectors. In order to assess the feasibility of this material a small scale study has been initiated.

This study includes:

1. fabrication and evaluation of Ge:Be detectors from existing material
2. analysis of the detector material.

This study (being carried out by Santa Barabara Research Center (SBRC) and the Naval Research Laboratory (NRL)) will be completed in September 1976 and should indicate whether Ge:Be detectors will be satisfactory for use in IRAS. The parameters shown in table 4.6 for Ge:Be are estimates of expected performance. In order that thermal generation of free carriers be negligible, these detectors must be operated at temperatures $\lesssim 6.6$K.

60-120 μm Ge:Ga

Gallium doped Germanium detectors have been studied extensively by workers at NRL and Cornell University. The best reported NEP for a Ge:Ga detector is 2×10^{-15} W/Hz^{½} (at zero background) for a detector operating near 4.2K (Moore). The calculated quantum efficiency for this detector is 0.5 and the responsivity is 3-4 amp/Watt. The limiting noise in this detector was due to thermal generation of free carriers; thus presumably the low background performance would improve if the operating temperature were reduced. A feasibility study of Ge:Ga detectors has been initiated to investigate and improve their low background, low temperature

performance. This study (carried out by SBRC) includes fabrication and optimization of Ge:Ga material, investigation and optimization techniques for making electrical contacts to Ge:Ga material and construction and evaluation of a number of Ge:Ga detectors. This program (to be completed in August 1976) will provide a solid basis for assessment of the low background capabilities of Ge:Ga detectors. If these detecors are found to be satisfactory, further development for actual use in IRAS should be undertaken. In order that thermal generation of free carriers be negligible compared to the generation rate by photon ionization, the operating temperature for these detectors must be $\lesssim 3.3$K.

The last column in table 4.6 lists the frequency of operation for the IRAS survey detectors. This frequency ($\sim$1 Hz) is substantially below the normal operating frequencies for these detectors. Laboratory measurements on doped silicon detectors indicate that the desired sensitivity can be achieved down to about 1-3 Hz with no interference from 1/f noise. However, the detectors should be evaluated to much lower frequencies ($\sim$0.01 Hz). The two long wavelength channels will operate at particularly low frequencies. The very low frequency operation under low background conditions of Ge:Be and Ge:Ga detectors will be determined as part of the evaluation of these detectors.

There are several options available in the choice of detectors for the survey channels. A very interesting alternative for the 8-15 μm channel is PbSnTe photovoltaic detectors. PbSnTe detectors offer the possibility of very high quantum efficiency, exceedingly low power dissipation, strong rejection of short wavelength radiation and high temperature operation (to 20K). In addition, the volume of a PbSnTe detector is very small; thus it is expected that particle radiation hits would be less of a problem for these detectors, although few data exist on the subject. The use of PbSnTe detectors for the 8-15 μm channel should be investigated further.

Bolometers

Bolometers are needed for the 120-300 μm channel. Germanium bolometers have been used for many years and are commercially available from Infrared Laboratories. Assuming a focal plane temperature of 3K, maximum permissible time constant of 50 ms, and detector size of 0.5 x 0.5 x 0.2 mm, a detector electrical NEP of $\sim 2 \times 10^{-14}$ $\mathrm{wHz}^{-\frac{1}{2}}$ could be achieved.

Two new types of bolometers currently under development in research laboratories offer the promise of perhaps an order of magnitude lower NEP at 3K for the same area and time constant, but neither has yet reached the stage of being used in astronomical detection systems. The first of these is an Indium film superconducting transition edge composite bolometer being developed by Clarke (U. C. Berkeley). The superconducting film is evaporated onto a thin diamond or sapphire substrate, producing a very low heat capacity structure. The substrate is blackened to radiation by coating with a resistive film. This bolometer has a low dc impedance and requires a special superconducting pre-amplifier to achieve optimum performance.

The second new type of bolometer is an ultra-thin silicon bolometer being developed by Weiss (M.I.T.) with support from Lincoln Laboratories. The basic idea here is to photo-etch a thin bolometer (∿5 μm thickness) and supporting threads from a single silicon wafer. Doping for the desired resistance and temperature coefficient of resistance are done by ion implantation. Test results have already verified that low noise thermometric elements can be produced with these techniques. This bolometer is very promising because it uses standard pre-amplifiers and could be mass produced with standard industrial techniques.

Finally, it should be mentioned that substantial improvement in bolometer performance can be achieved if the focal plane is operated at temperature <3K.

Infrared Background

Since the ultimate sensitivity of the proposed system is generally limited by the photon fluctuations in the zodiacal background emission, an addendum describing that background is appropriate.

It was recognized by Harwit (Liege Symposium 1962), that the thermal emission of the zodiacal dust particles is potentially a strong background noise source. Only preliminary measurements of the background, all at an elongation angle near 90°, exist at this time (Soifer, Houck, and Harwit, Ap. Letters 1971, Briotta and Houck, 1976).

The measurements indicate a color temperature of ≈ 300K with marginal evidence for a silicate emission feature. The highest flux level observed at ~ 10 μm is $\sim 6 \times 10^{-11}$ W/cm^2 μ sr. The 100 μm flux is less by a factor of ~ 300, while at 100 μm the diffuse galactic radiation in the galactic plane is several times stronger than the zodiacal emission (Pipher 1972 IAU Symposium 52). The observed zodiacal measurements are in rough agreement with the infrared flux calculated on the basis of the visible brightness of the zodiacal light by assuming the zodiacal particles have the same optical characteristics as cometary dust. The largest contribution to the infrared flux is from particles within 2 A.U. of the earth. The flux levels near the ecliptic pole are 3-5 times less than the corresponding value in the ecliptic plane.

6. THE AFCRL SKY SURVEY

In 1971-1972, the Air Force Cambridge Research Laboratory conducted an infrared sky survey (AFCRL Survey) in a series of seven rocket flights utilizing a cryogenically cooled telescope. The catalog resulting from this survey has been examined carefully by astronomers, including extensive efforts to confirm previously unidentified sources.

Because a number of problems were encountered in attempting to confirm new sources, and because this program represents a previous technological experience very relevant to the IRAS mission, a study was undertaken to examine the AFCRL program in detail. The aim of this task was to identify, if possible, plausible explanations for the difficulties encountered in confirming AFCRL sources, to draw on the experience gained in this program to guide design of the IRAS mission and instrument, and, ultimately, to provide a basis for judging the feasibility of conducting a more sensitive infrared sky survey from a satellite. A detailed discussion of this investigation is contained in a separate report (Hauser, Low, Rieke, Price), which should be consulted by those interested in this subject. Only the conclusions as they relate to IRAS planning will be summarized here:

a. the confirmation difficulties and apparent anomalies in the CRL catalog can be explained, at least in part, in terms of problems encountered in executing the mission and choices made in analyzing its results;

and

b. the IRAS instrument, mission profile, and data processing can be deigned to overcome the problems of the AFCRL survey.

Leaving detailed support for the conclusions to the report, we list here the implications for the IRAS mission.

First, when presenting any of the results of the IRAS survey, every care should be taken to specify fully the criteria, both philosophical and technical, used to prepare them. Clear definition of the confidence to be attached to the results, or cautions to be exercised in their use, should be provided.

Second, a high degree of self-confirmation (i.e., redundancy) must be rigorously maintained in the source-identification algorithm. The present plan for the IRAS mission, including observational redundancy on time scales of the order of seconds, hours, weeks, and months, provides a basis for rejecting all of the spurious effects identified in the CRL survey. The data processing algorithm must rigorously apply all of the internal consistency checks made possible by these data to assure the quality of the end result.

Third, though computers must of course do the bulk of the data processing, extensive comparison must be made between machine decisions made on real data with the judgments of astronomers looking at the same data. This should be done not only at the beginning of the mission, but on a sampled basis throughout the mission to assure the ability of the programs to handle all contingencies in the data stream.

Fourth, baffling of the sensor against side-lobe response to warm local sources should be adequate to assure negligible contribution to detector noise from these sources.

Fifth, the detector shielding and electonics should be designed to minimize and remove signals induced by energetic particle radiation.

The important lesson emerging from this study task is that previous infrared survey experience has revealed no fundamental obstacles to the planning and execution of a high sensitivity, high reliability, unbiased survey of the infrared sky.

VII. SCHEDULE AND COST

A. SCHEDULE

INTRODUCTION

The schedule presented here represents the best estimate of a feasible means for the realization of the Infrared Experiment (IRX) instrument. It considers the phases of procurement, development, test and integration, launch, and data reduction. The schedule, leading to a launch in February 1981 is considered difficult yet realistic if certain near-term key milestones are achieved. The IRX development may be said to be on the critical path of the IRAS program schedule. The two critical milestones of concern are the issuance of a Request for Proposal (RFP) on August 1, 1976, and the subsequent award of a development and production contract on February 1, 1977. To achieve this will require an extraordinary effort on the part of NASA Centers concerned to expedite the preparation and issuance of the RFP. Failure to adhere to this schedule could result in a day-for-day slippage in the IRAS program schedule and launch. There will be associated cost increases to the Netherlands resulting from any such IRX slip. Beyond a certain date the launch window may have to be reset for one half year later due to special orbital considerations.

SCHEDULE DISCUSSION BY LINE NUMBER

1. Final JMDT Study Report.

The report of which this schedule is a part is in accordance with a NASA HQ request to provide such a report at the beginning of May 1976.

2. Memorandum of Understanding.

It is planned that NASA and NIVR will negotiate the necessary Memorandum of Understanding (MOU) which will detail the responsibilities of the several concerned parties and will include project management provisions deemed necessary for successfully executing the overall IRAS program. The target date for signing such agreement is July 1, 1976.

3. IRX RFP Issuance.

As noted above, in order to insure a reasonable time for design and development, qualification and delivery of the protoflight IRX, a Request for Proposal will be released by NASA on August 1, 1976. The RFP will include technical specifications and performance requirements together with schedule requirements compatible with the IRAS program.

4. Preliminary Spacecraft Design.

During this time the spacecraft conceptual design will be sufficiently firmed up to permit the definition of the IRAS spacecraft - IRX interface.

5. IRX Proposal Evaluation and Contract Award.

Proposals from industry will be received on 1 October 1976. Technical and cost evaluation, selection of one proposal, and negotiations with the selected contractor would occur during this period. Award of the contract will occur on 1 February 1977. This will allow 32 months from contract start to delivery of a Qualified Protoflight Infrared Instrument to ICIRAS.

6. S/C Engineering Models, Design, Fabrication and Test.

Develop and build suitable Structural, Thermal and Electrical models of the spacecraft. Perform appropriate engineering tests to confirm subsystems and system performance, compatibility and interfaces.

7. S/C GSE Design and Fab.

Develop and build all required ground support equipment required for spacecraft system handling, testing, and checkout.

8. IRX Design.

The detailed design of the Infrared Experiment (IRX).

9. System Requirements Review.

An overall system level review of the complete IRAS system requirements specification.

10. IRX Engineering Models Fab and Test.

Fabricate, assemble and test development engineering models of the Infrared experiment.

11. Preliminary Design Review.

Full review of the design concept of the spacecraft and experiment.

12. IRX Protoflight Model Fab.

Fabrication and assembly of the protoflight model of IRX experiment.

13. Subsystem Design Reviews.

Separate reviews of the design of each subsystem including IRX experiment.

14. S/C Protoflight Model Design and Fab.

Design, fabrication and assembly of all subsystems of the protoflight spacecraft.

15. Critical Design Review.

A detailed review of the IRAS system including all subsystems, experiments, test, support, launch, and operations. Followed by design freeze.

16. IRX Protoflight Qualification and Calibration.

This period covers the mechanical, electrical and thermal qualification of the Protoflight Infrared Experiment. Also included is the necessary performance calibration tests of the experiment. At the completion of calibration, the experiment will be shipped to ICIRAS for integration with the IRAS spacecraft.

17. Integration and Test.

At the beginning of this period, the IRX will be integrated with the spacecraft. The assembled system will then undergo the complete qualification program. This will consist of all RFI, thermal, mechanical, and electrical environmental tests necessary to qualify the IRAS spacecraft for flight.

18. Data Reduction Software Design and Development.

Preparation of computer software-programs to handle ground processing of IRAS spacecraft test and orbital data output.

19. Data Reduction Hardware Procurement.

Procurement of data processing equipment necessary to support the IRAS spacecraft test and orbital data acquisition phases.

20. Pre-Environmental Review.

Review of the spacecraft integration results before proceeding with environmental testing, including environmental test plans.

21. Flight Readiness Review.

Review of the environmental test results and determination that the integrated spacecraft is ready for shipment to the launch-site.

22/23. Launch Preparations and Launch.

Field preparation of the integrated, qualified spacecraft including installation on the launch vehicle and final launching into orbit.

24/25. IRAS Operations and Data Reduction.

In orbit spacecraft operations required to control the spacecraft and to collect, process and analyze all scientific and engineering data.

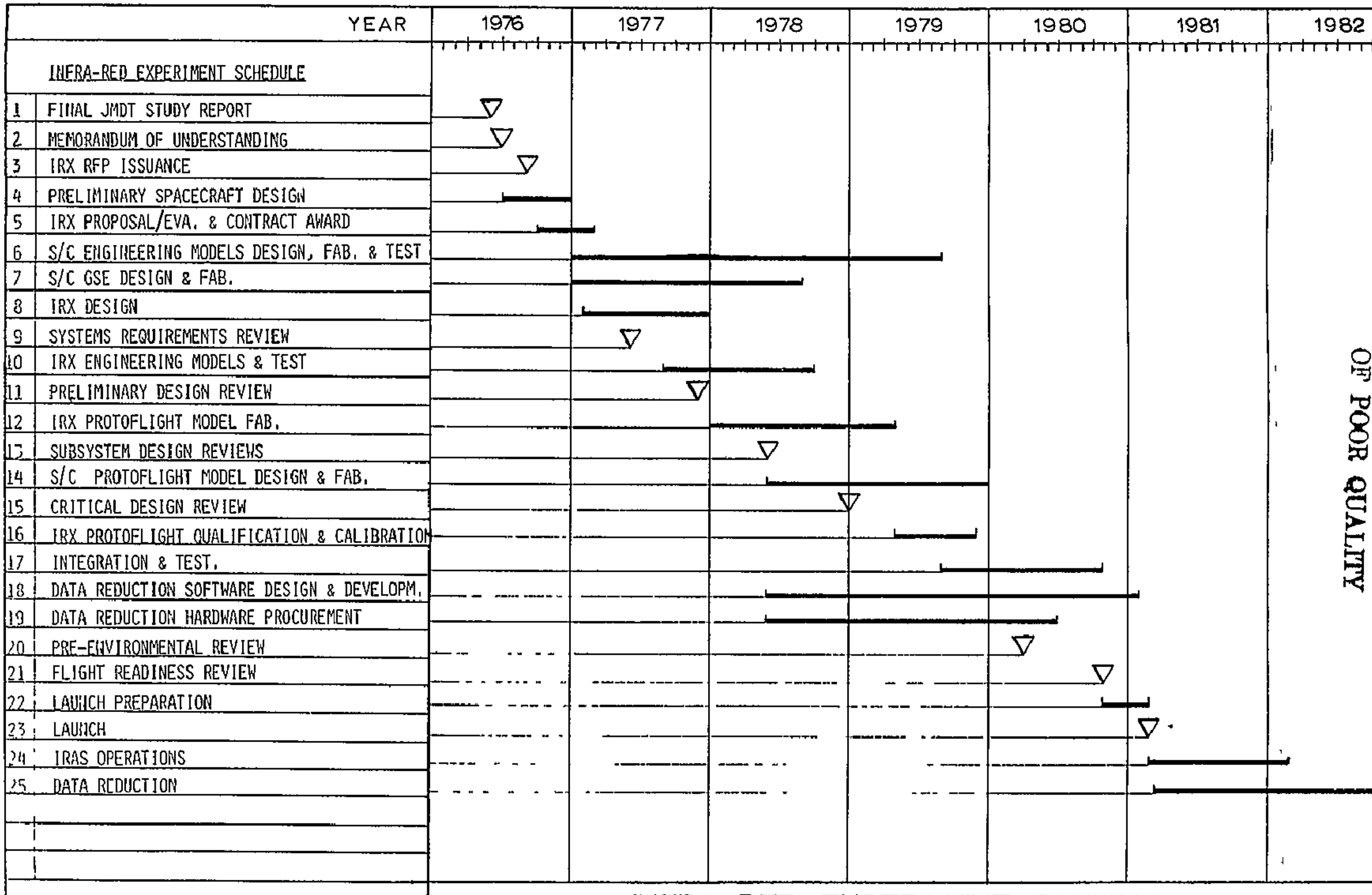
B. COST

During the last part of the study phase strong consideration has been given to the cost aspects of the project.

Substantial effort has been devoted to bring the cost of the system within the constraints conveyed to the mission definition team by the respective agencies.

It appeared that the major cost driving elements are the number of detectors and the number of bits generated per day. They are obviously related and reducing the number of detectors has caused a substantial cost reduction. It has also been necessary to reduce the size of the solid state memory. Several other options for cost reductions have been considered but the impact of these proved to be far smaller than the ones stated above. The conceptual design as presented in this document meets, according to the information at present available to the team, the cost constraints.

On the Dutch side, however, the cost estimate is very close to the appropriate limit. Certainly, further simplifications have to be looked for to provide sufficient margin. The team is confident at this stage that this can be done without seriously affecting the scientific objectives.



INFRA-RED EXPERIMENT SCHEDULE

National Aeronautics and Space Administration

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland